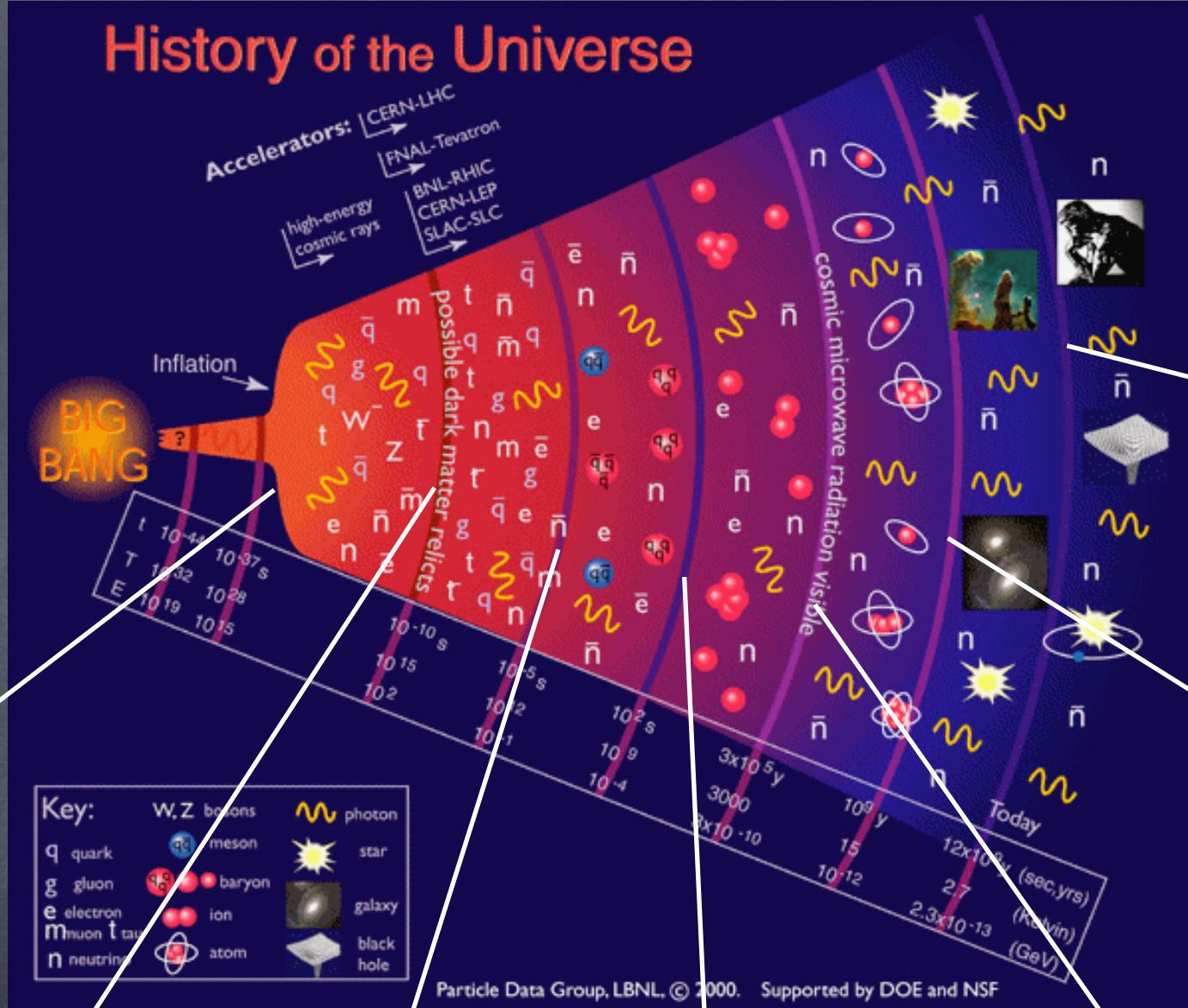


Cosmological Magnetic Fields

Chiara Caprini
IPhT, CEA Saclay (France)

History of the Universe



EW phase transition

QCD phase transition

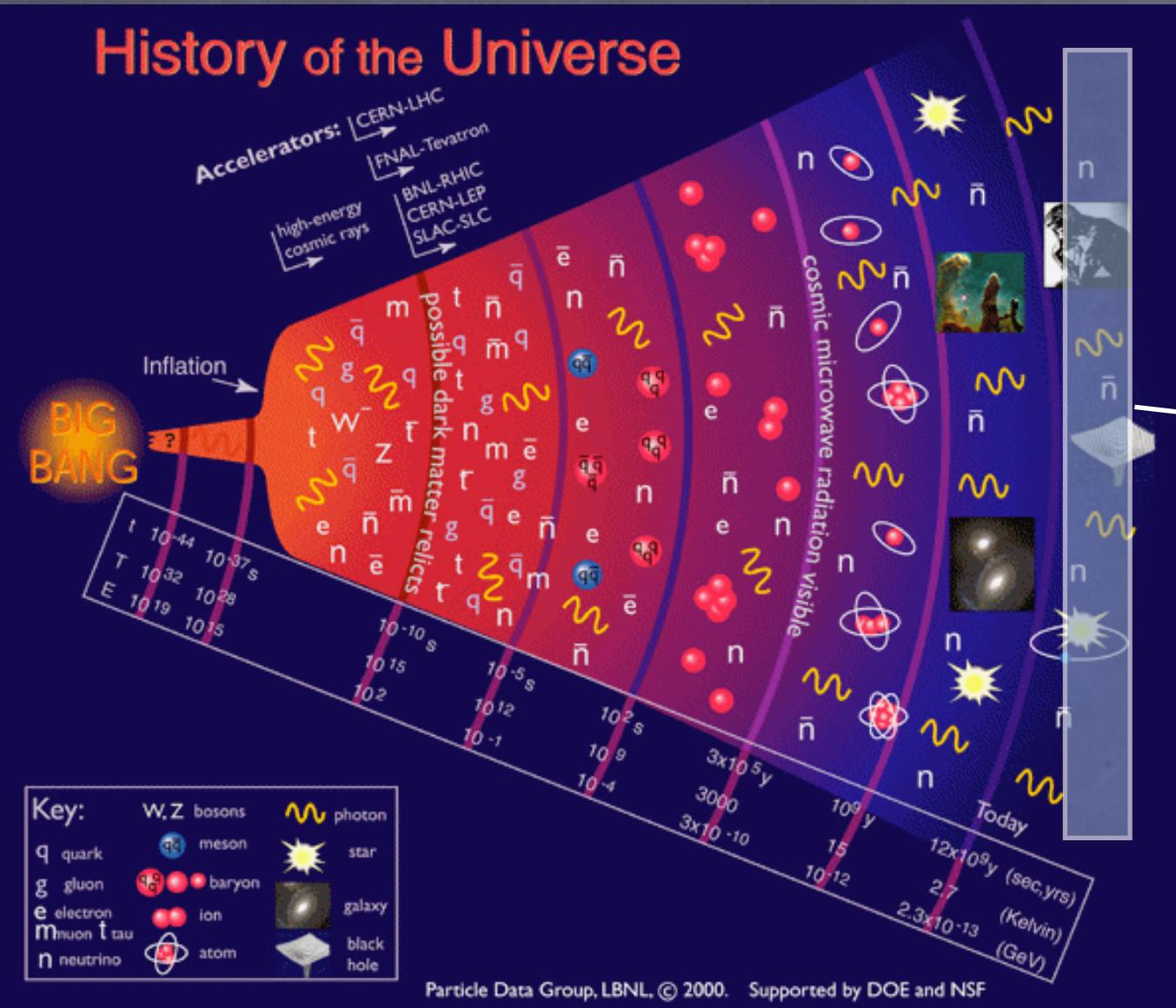
nucleosynthesis
neutrino decoupling
electron non relativistic

recombination
formation of the CMB
equality

today

structure
formation
reionisation

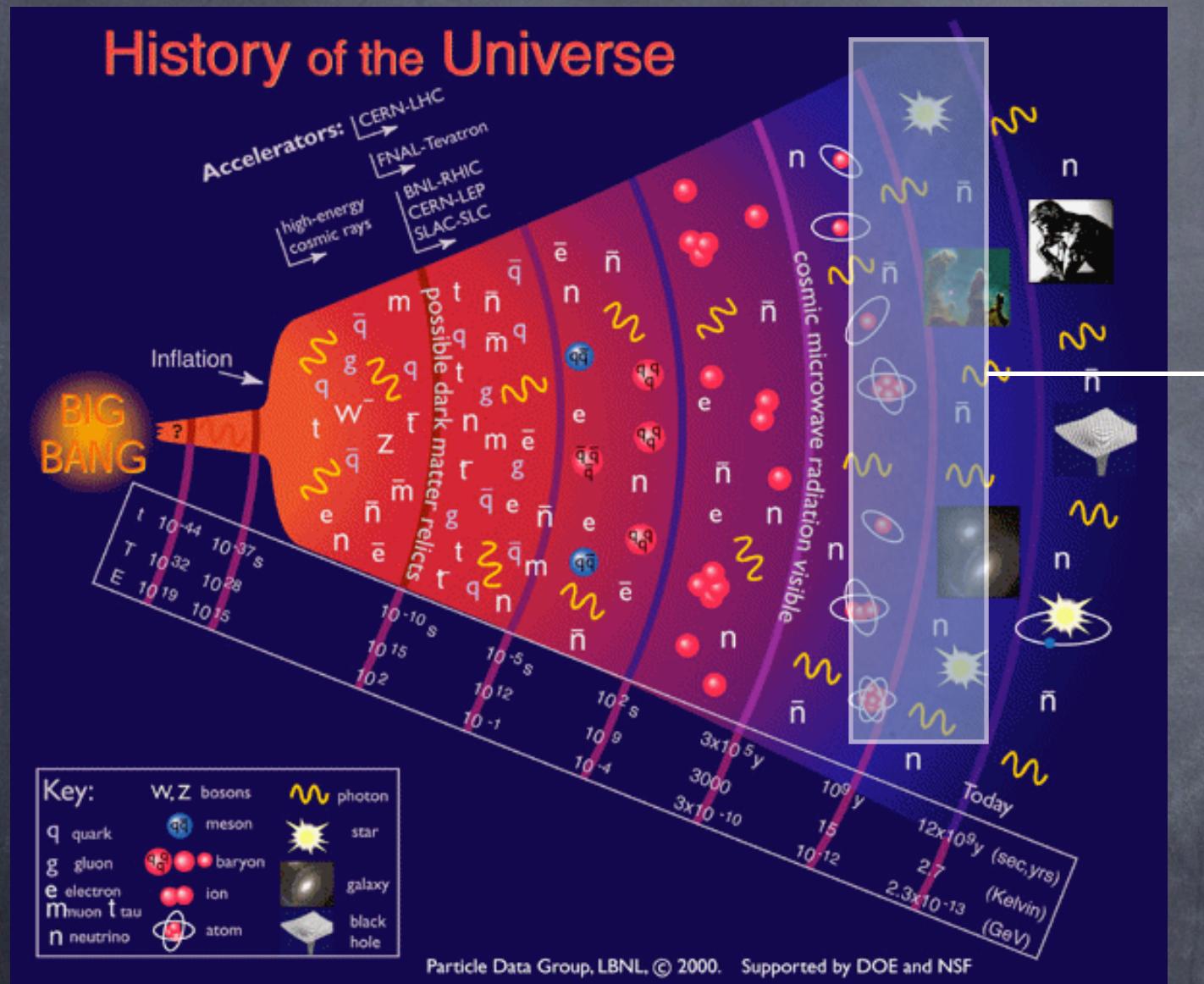
History of the Universe



- Today: large scale magnetic fields are observed in galaxies and clusters

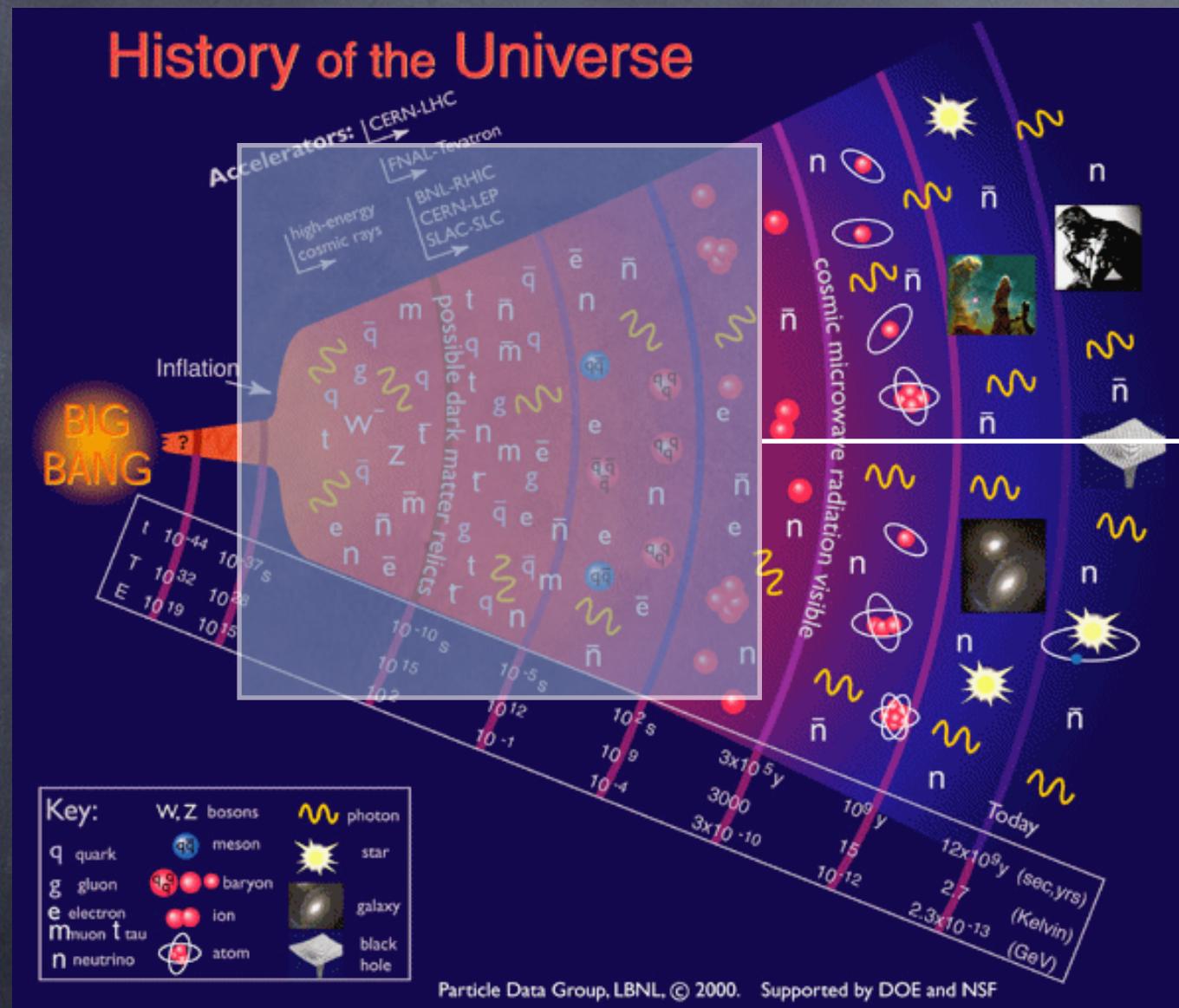
PROBLEM: WHAT IS THE ORIGIN OF THESE MAGNETIC FIELDS?

TWO POSSIBILITIES FOR THE ORIGIN:



GENERATED
DURING THE
FORMATION OF
STRUCTURES

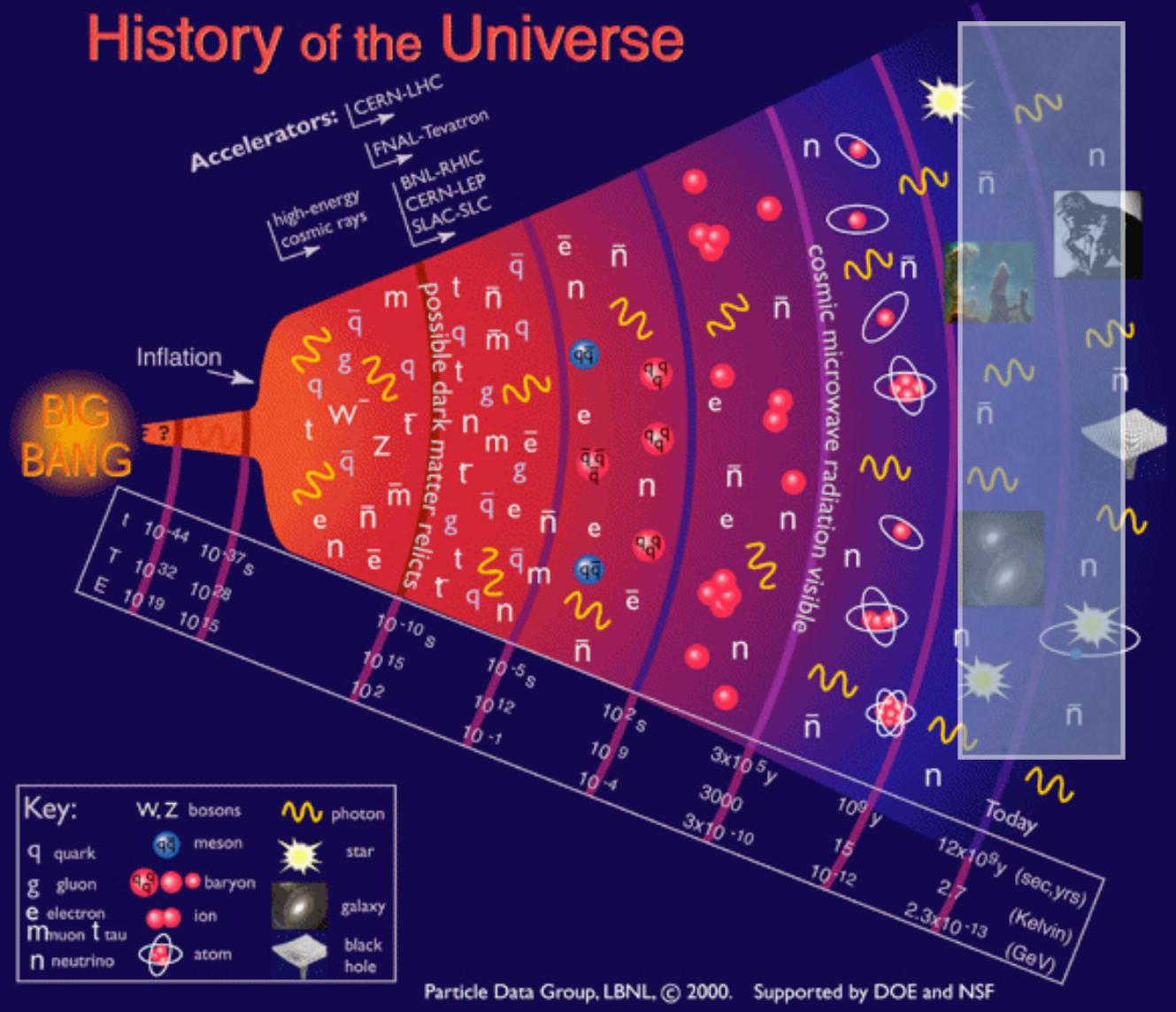
TWO POSSIBILITIES FOR THE ORIGIN:



GENERATED
IN THE
PRIMORDIAL
UNIVERSE

OUTLINE OF THE SEMINAR:

History of the Universe



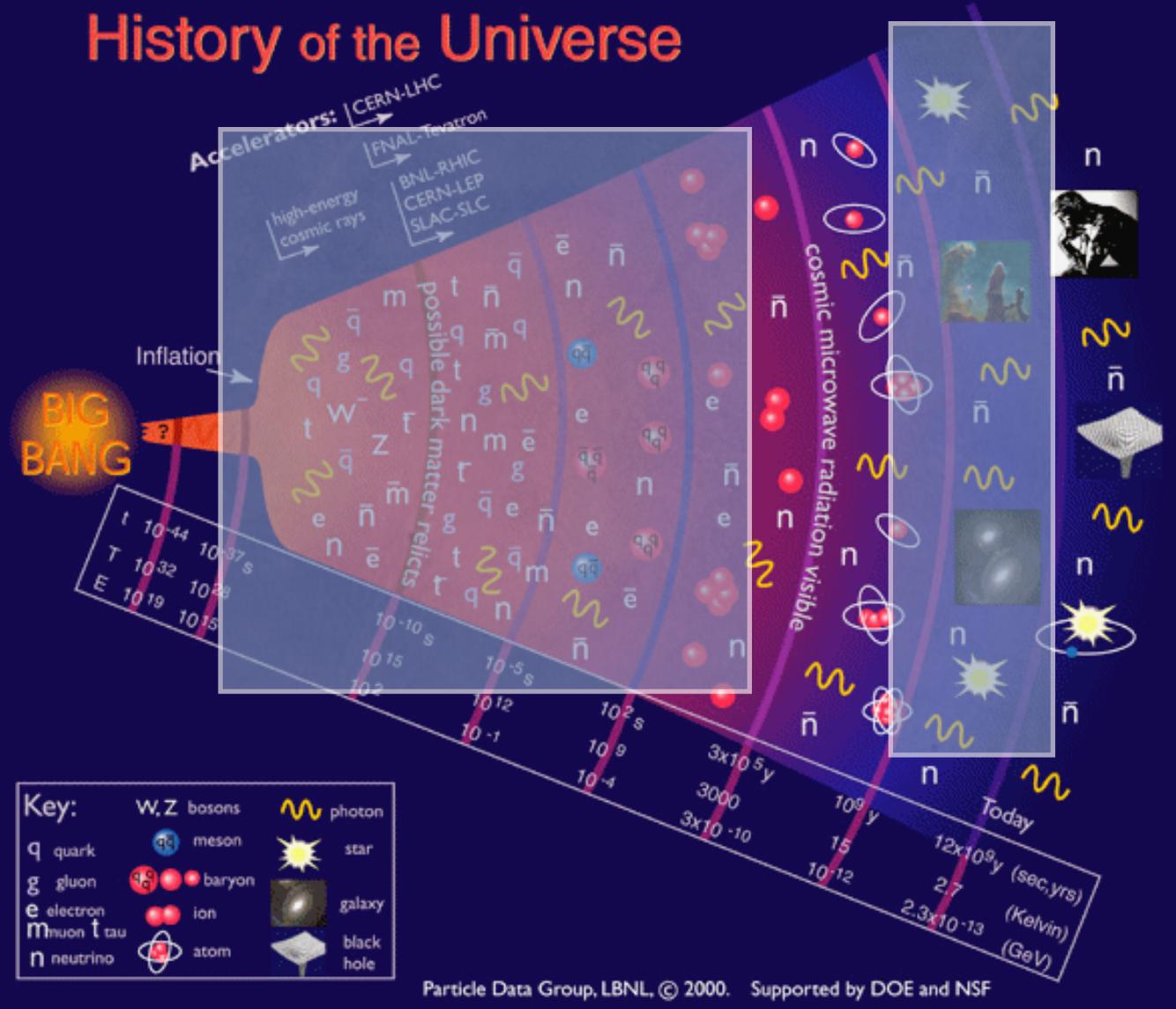
OBSERVATIONAL
TECHNIQUES

CHARACTERISTICS
OF THE FIELDS

AMPLIFICATION
DURING
STRUCTURE
FORMATION

OUTLINE OF THE SEMINAR:

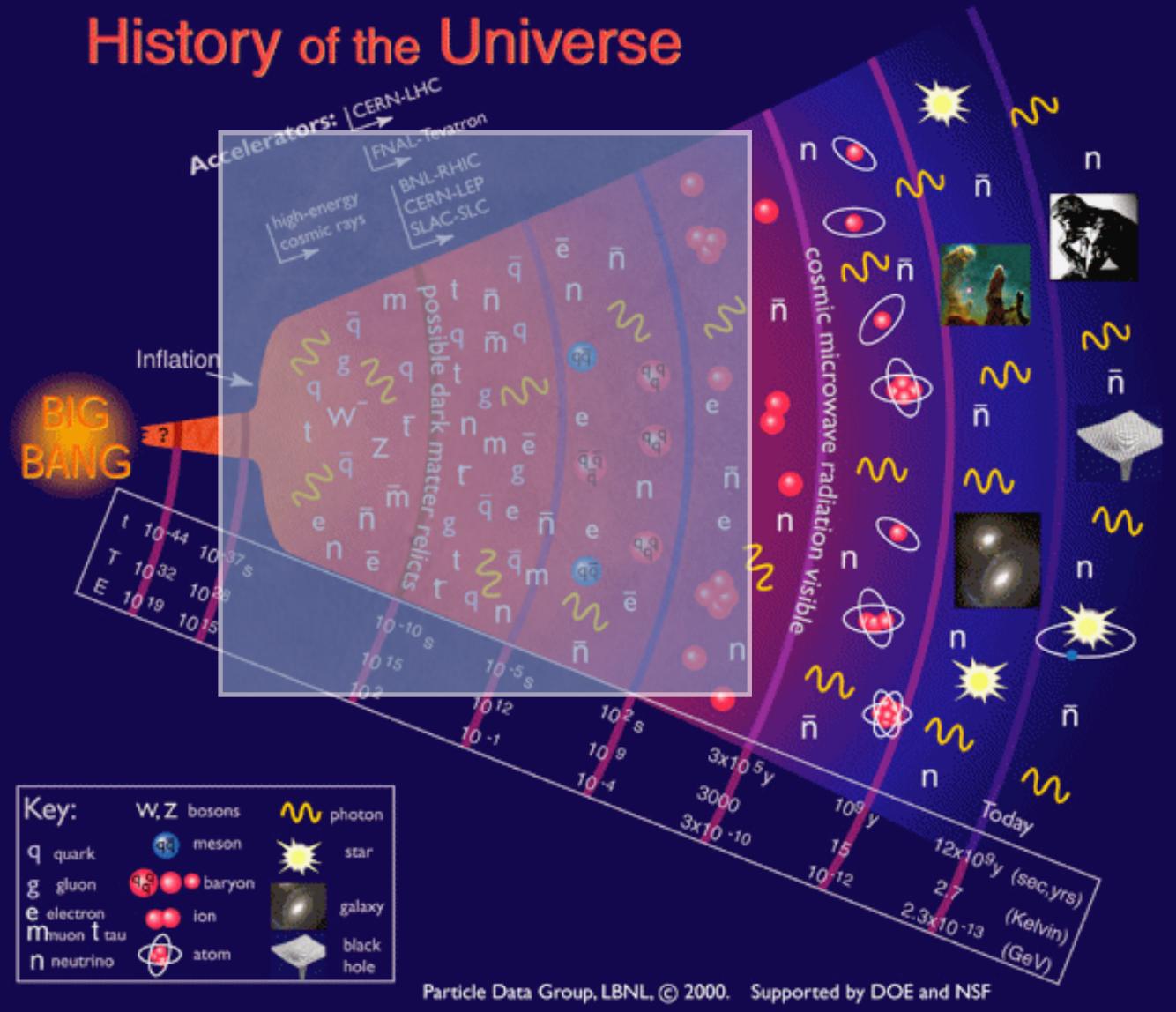
History of the Universe



POSSIBLE
GENERATION
MECHANISMS

OUTLINE OF THE SEMINAR:

History of the Universe



IF THEY ARE
PRIMORDIAL

EVOLUTION

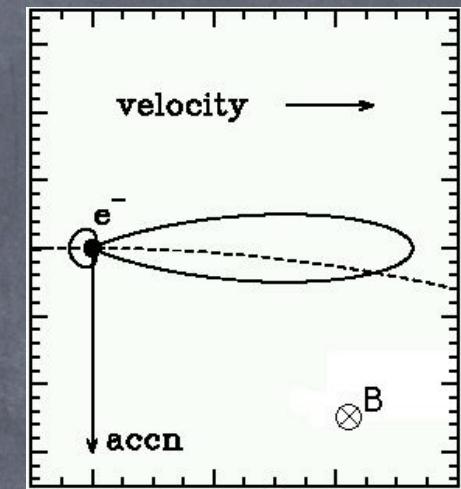
CONSTRAINTS

OBSERVATIONAL
EFFECTS

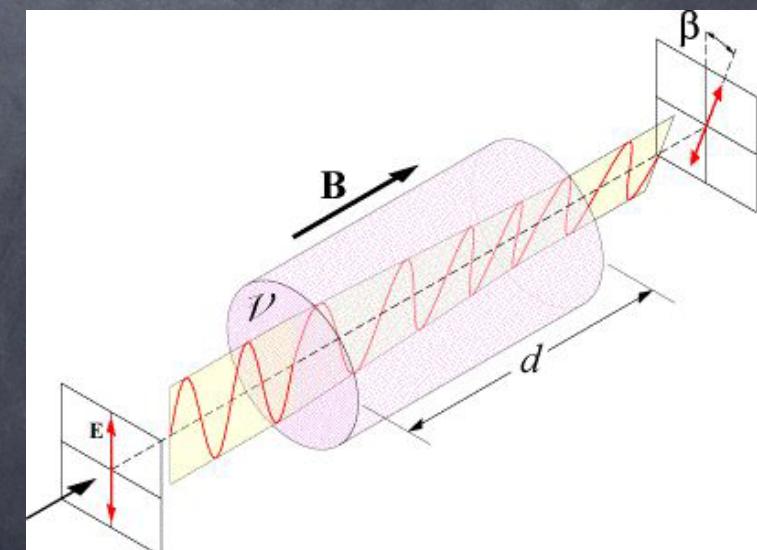
OBSERVATIONS – Techniques

- Zeeman splitting : direct measure from hydrogen emission lines used only for the Milky Way

- Synchrotron radiation :
plane of the sky component
requires independent measure of electron density



- Faraday rotation :
line of sight component
independent measure of electron density
several wavelengths (proportional to λ^2)



OBSERVATIONS – Galactic magnetic fields

General characteristics :

$$B_{\text{tot}}^2 = B_{\text{u}}^2 + B_{\text{r}}^2$$

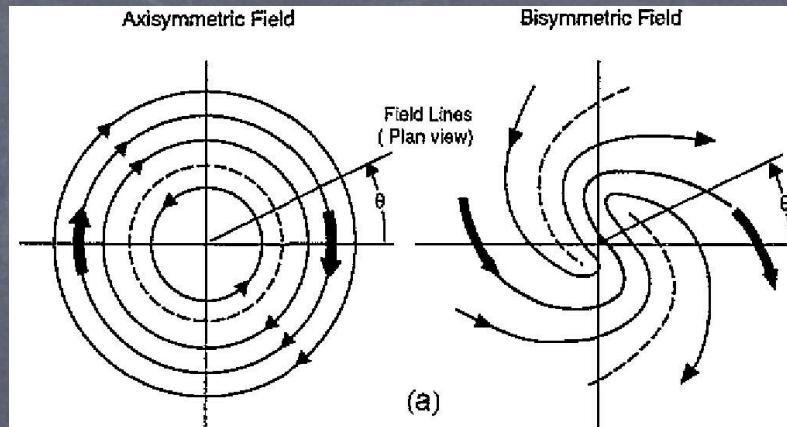
$$B_{\text{u}} \simeq \mu\text{G}$$

$$B_{\text{r}} \simeq \text{several } \mu\text{G}$$

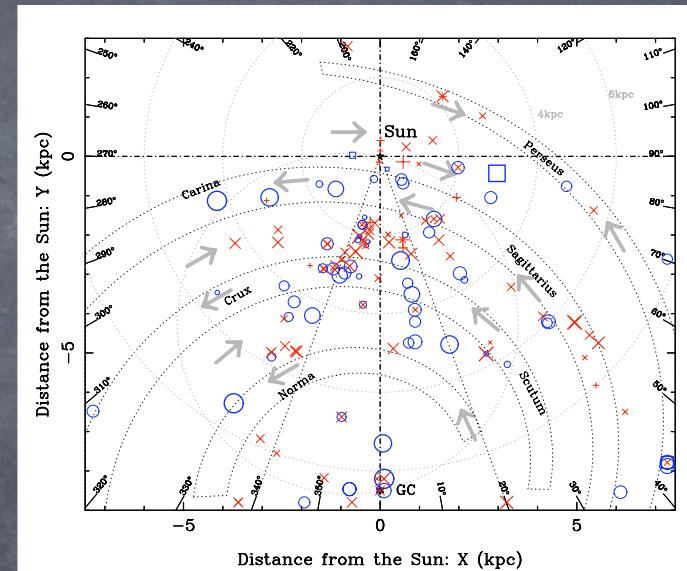
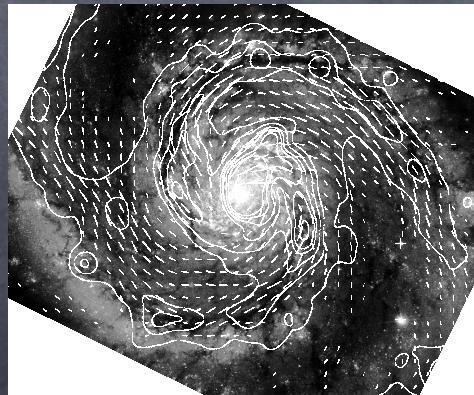
$$\ell_{\text{corr}} \simeq \text{kpc}$$

Structure :

- Axisymmetric or bisymmetric?



- Equipartition holds?



M51

Zweibel and Heiles 1997,
Han 2007, Jaffe et al 2009...

- Dynamically important and not yet completely understood

OBSERVATIONS – Cluster magnetic fields

General characteristics :

$$B \simeq \mu\text{G} \quad \ell_{\text{corr}} \simeq 1 - 100 \text{ kpc}$$

Examples :

- Synchrotron emission of cluster wide diffuse sources: COMA

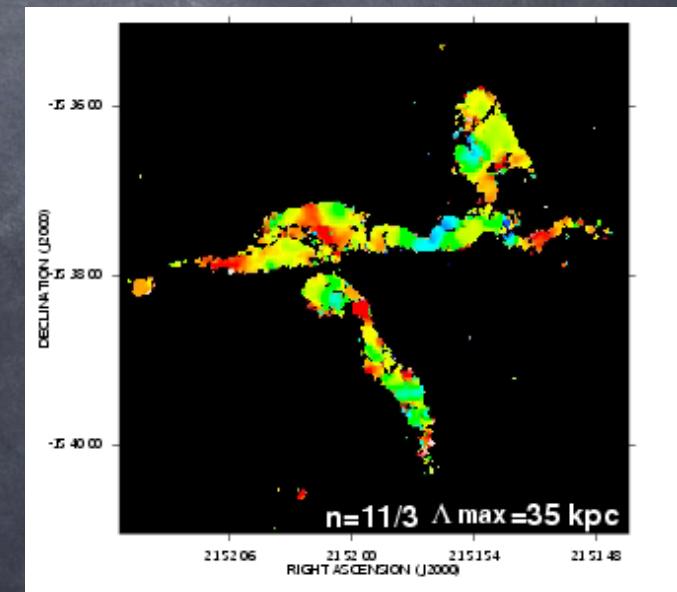
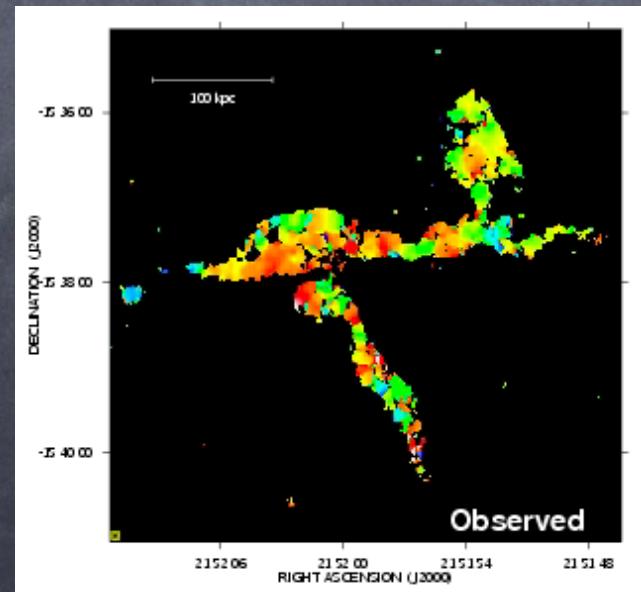
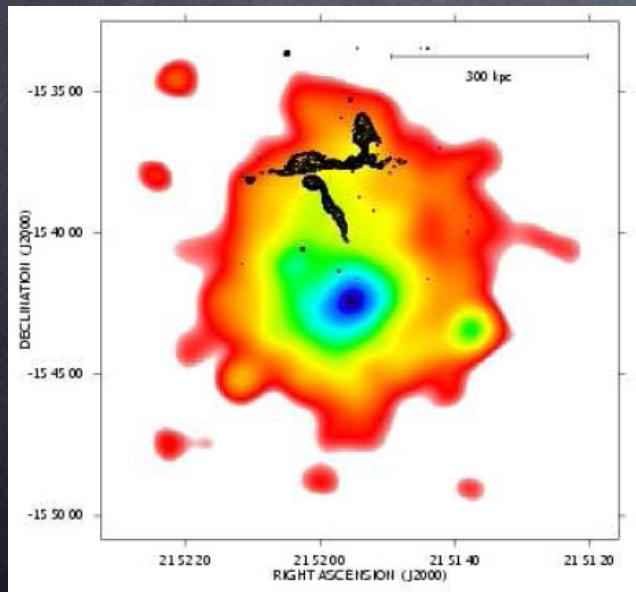
Average value: $B \simeq 0.1 - 1 \mu\text{G}$

Carilli and Taylor 2002,
Thierbach et al 2003

- Faraday rotation of radio sources inside or behind the cluster + X-ray observation of the hot gas + simulated RM maps assuming a MF model

Abell 2382

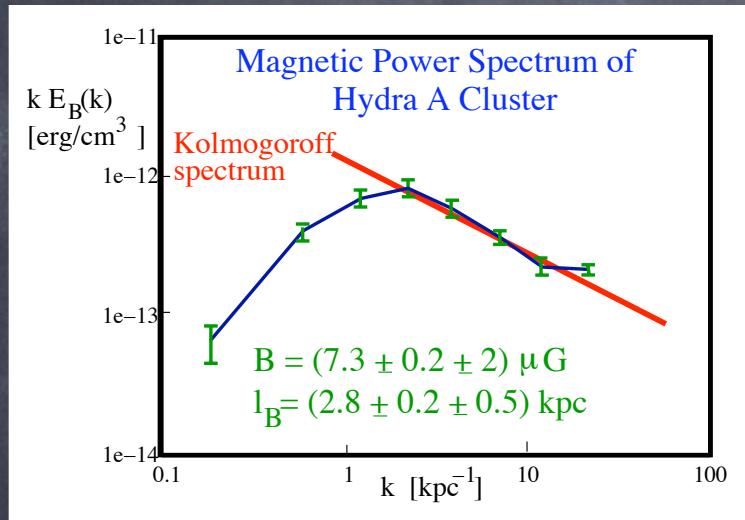
Guidetti et al 2007



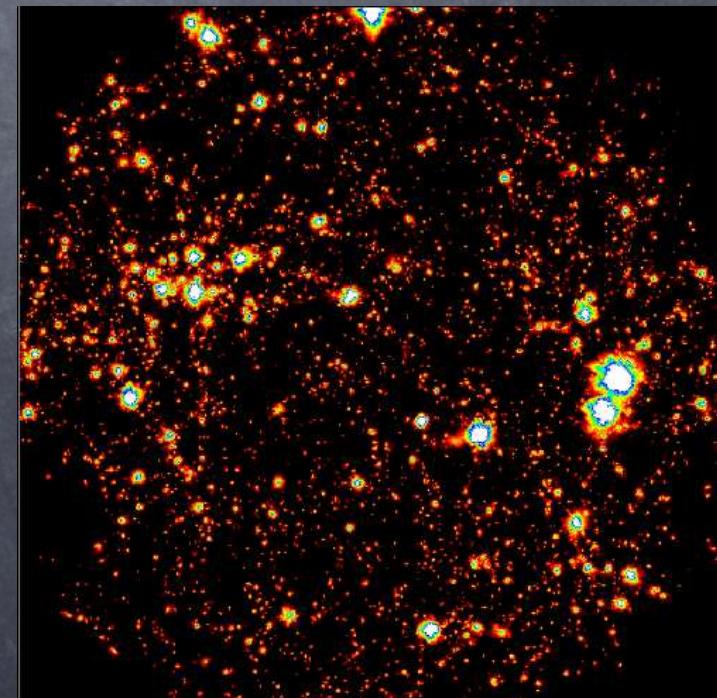
OBSERVATIONS – Cluster magnetic fields

Abell 2382 : $B \simeq 3.3\mu\text{G}$ $\Lambda_{\text{max}} \simeq 35\text{kpc}$ Kolmogorov spectrum

For the COMA cluster, results in agreement with synchrotron Bonafede et al 2010



Hydra A : Vogt and Ensslin 2005
 $B \simeq 7\mu\text{G}$ $\Lambda_{\text{max}} \simeq 3\text{kpc}$



• Very detailed MHD simulations

Dubois and Teyssier 2008, Donnert et al 2008...

$B \simeq 5\mu\text{G}$
200 Mpc

OBSERVATIONS – High redshift and intergalactic

High redshift objects : Athreya et al 98, Pentericci et al 02, Kronberg et al 07...

Faraday rotation in radio proto-galaxies
and quasars at $z > 2$

$$B \simeq \mu\text{G} \quad \ell_{\text{corr}} \simeq \text{kpc}$$

Intergalactic magnetic field : LOWER BOUND by Fermi

Cascade of TeV gamma rays by a distant point source can be deflected by
the extra-galactic magnetic field \longrightarrow measurable effects in the shape
and flux of the point source

Neronov and Vovk 2010, Tavecchio et al 2010, Ando and Kusenko 2010, Dolag et al 2010

$$B \gtrsim 5 \cdot 10^{-15} \text{ G}$$

First claimed detection of MF in IGM

OBSERVATIONS – Summary

- ⦿ Magnetic fields of order microGauss in all observed objects
- ⦿ Correlated on scales of the order of the object size
- ⦿ Probably grown in short times (or present previously)
- ⦿ Probably present also in voids outside galaxies and clusters

$$\Omega_B = \frac{B^2}{\rho_c} \simeq 0.06 \Omega_{\text{rad}} \left(\frac{B}{\mu\text{G}} \right)^2$$

Sun: 1 G, Earth: 1/2 G

Amplification during structure formation

High electrical conductivity \longrightarrow Conservation of magnetic flux

- Amplification by structure collapse :

$$B_{\text{fin}} = B_{\text{in}} \left(\frac{L_{\text{in}}}{L_{\text{fin}}} \right)^2 = B_{\text{in}} \left(\frac{\rho_{\text{fin}}}{\rho_{\text{in}}} \right)^{2/3} \quad B_{\text{in}} \simeq 10^{-9} \text{ Gauss}$$

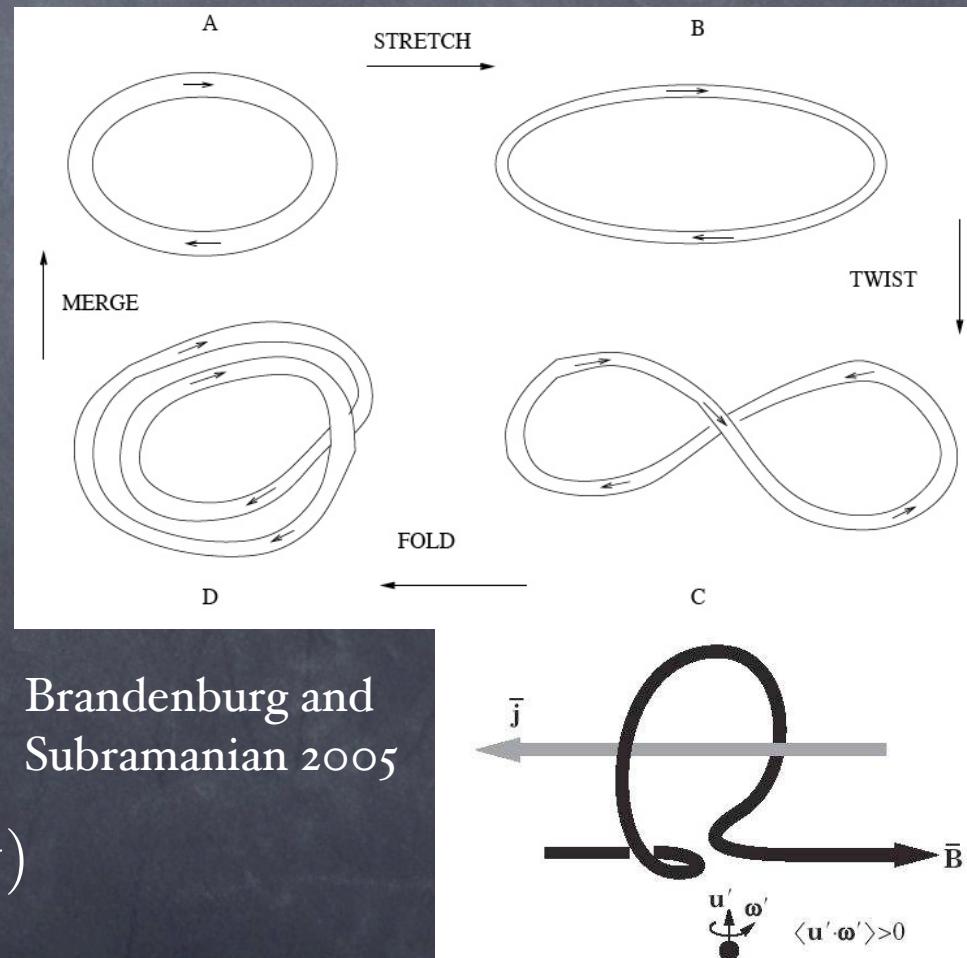
- Amplification by galactic dynamo :

INGREDIENTS high conductivity
turbulence
differential rotation

RESULTS exponential growth to
equipartition, axisymmetric

PROBLEMS needs many rotations,
reaches saturation?

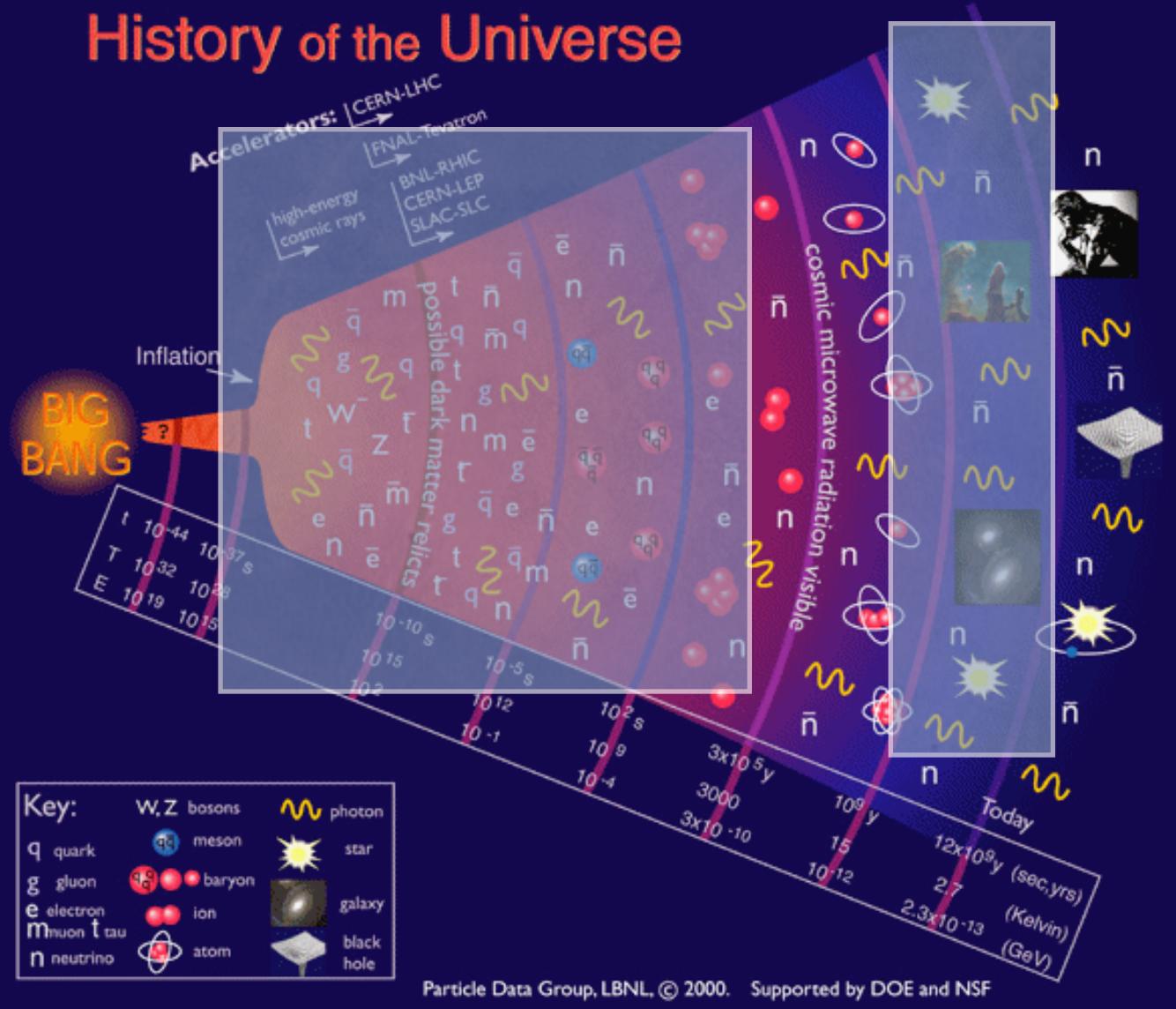
$$B_{\text{in}}^{\text{gal}} \simeq 10^{-21} \text{ Gauss} \quad (t_{\text{gal}} \simeq 10 \text{ Gy})$$



Brandenburg and
Subramanian 2005

OUTLINE OF THE SEMINAR:

History of the Universe



POSSIBLE
GENERATION
MECHANISMS

GENERATION MECHANISMS

$$B \simeq 10^{-9} \text{ Gauss} \quad \text{or} \quad 10^{-21} \text{ Gauss} \quad \text{at about 100 kpc}$$

- Generation after recombination

- good: ‘standard’ physics

- bad: non-linear physics, correlation scale too small

- Generation prior to recombination

- CAUSAL good: quite easy to get

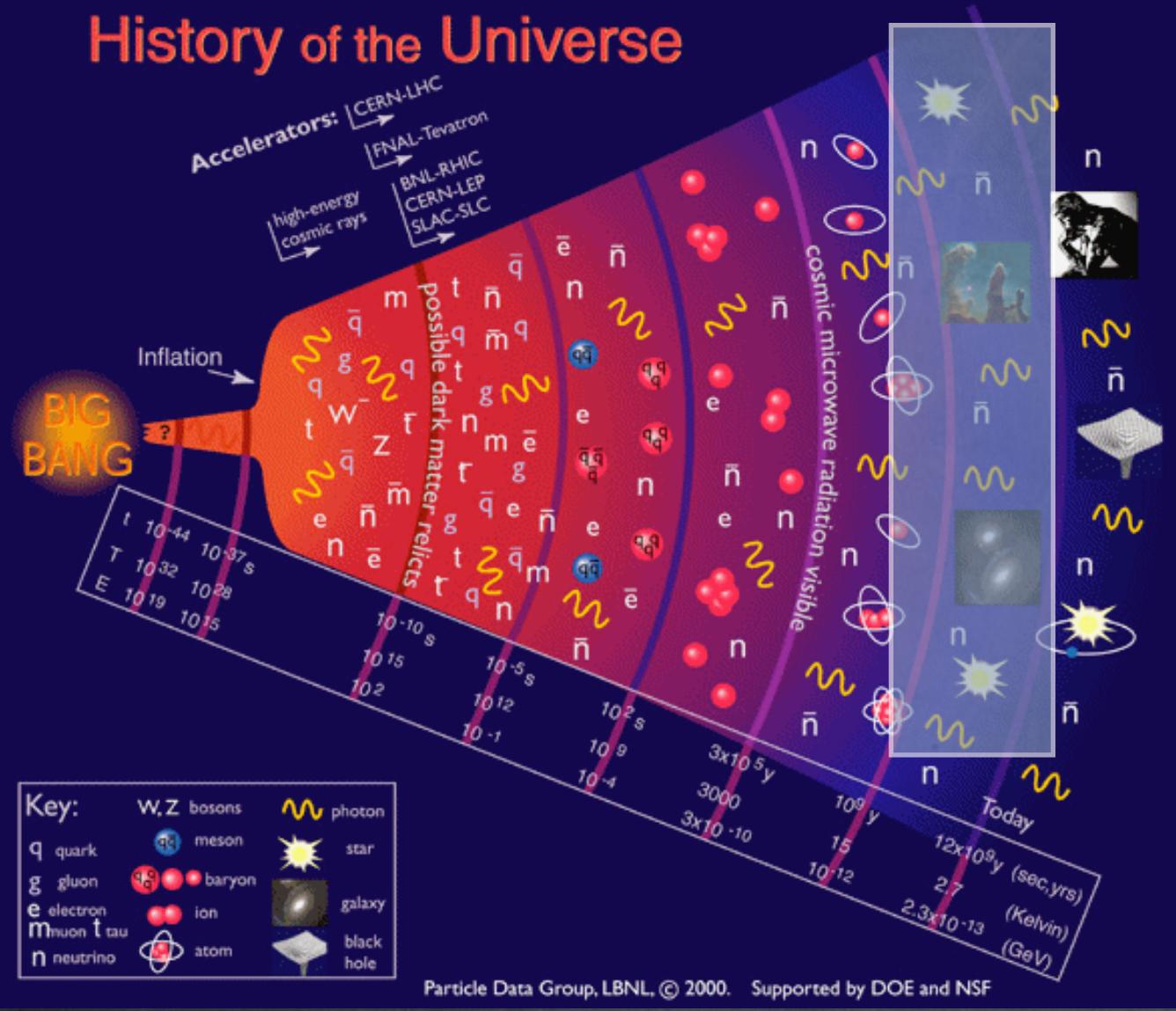
- bad: correlation scale too small

- A-CAUSAL good: generated at any scale

- bad: not very predictive

more than 100 proposed mechanisms but no preferred one

History of the Universe



GENERATION
AFTER
RECOMBINATION

Generation after recombination

- **BIERMANN BATTERY**

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{v} \times \mathbf{B} - \frac{\Delta \mathbf{B}}{4\pi\sigma} - \frac{\nabla n_e \times \nabla P_e}{en_e^2}$$

galactic: shocks by SN explosions in proto-galaxies (problem: scale)

both: radiation pressure at reionisation + density fluctuations of forming structures

- **CLUSTERS: SMALL SCALE TURBULENT DYNAMO**

open questions: what generates it (mergers)?

scale (reversal of the field, Faraday rotation)?

saturation?

- **EJECTION** galactic: from stars

cluster: from galaxies and/or AGN

(open questions: mix? amplitude? maintenance?)

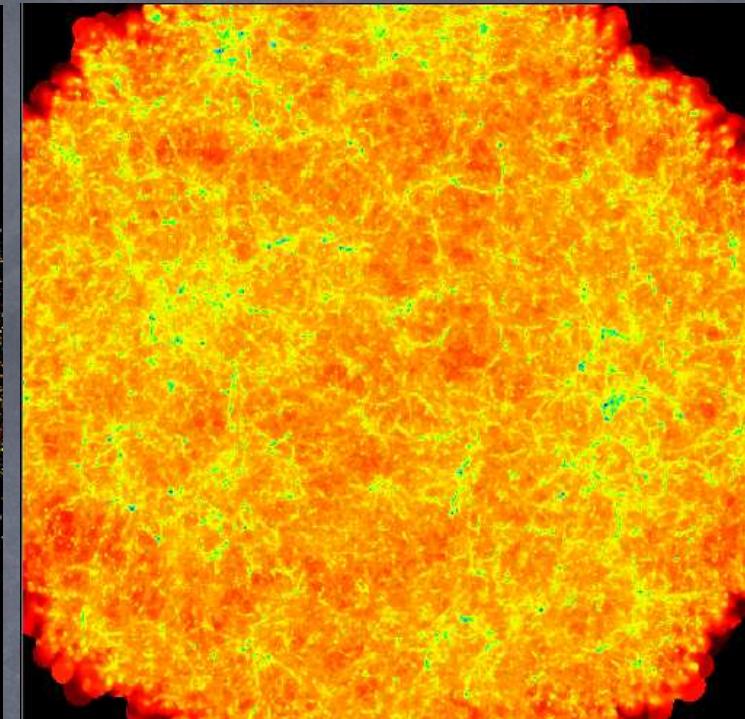
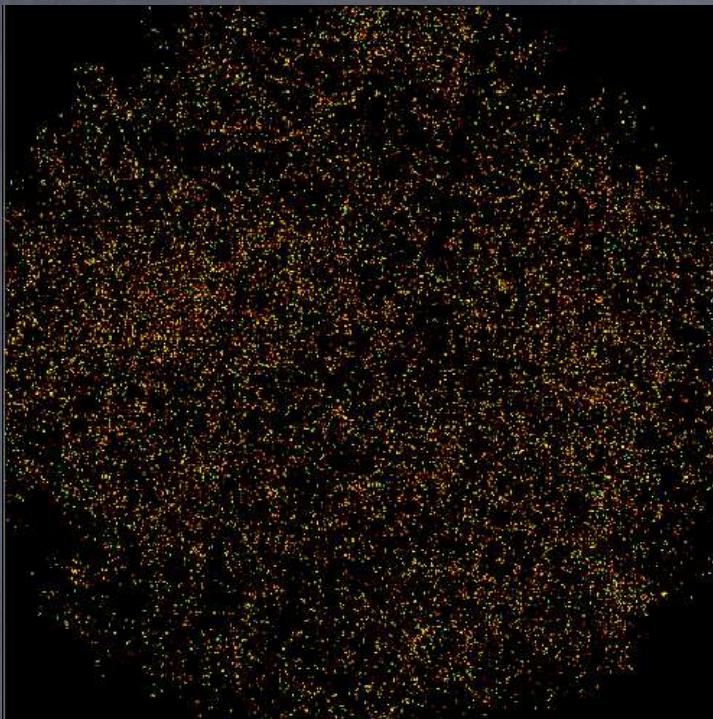
Hanayama et al 2005, Biermann and Galea 2003, Langer et al 2005, Colgate and Li 2000, Subramanian 2008, Schekochihin and Cowley 2005, Xu et al 2009, Miniati and Bell 2010...

MHD simulation
(Donnert et al
2008):

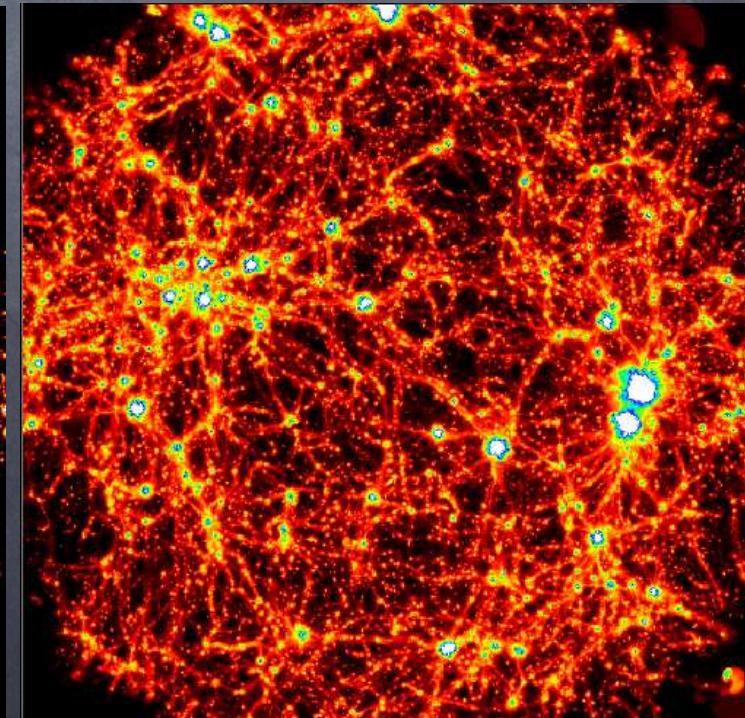
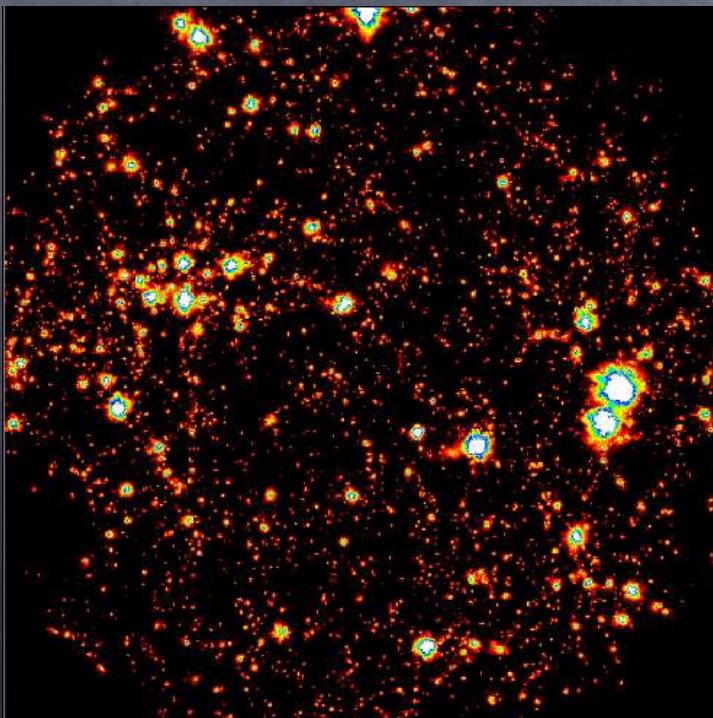
EJECTION

PRIMORDIAL

$z=4$



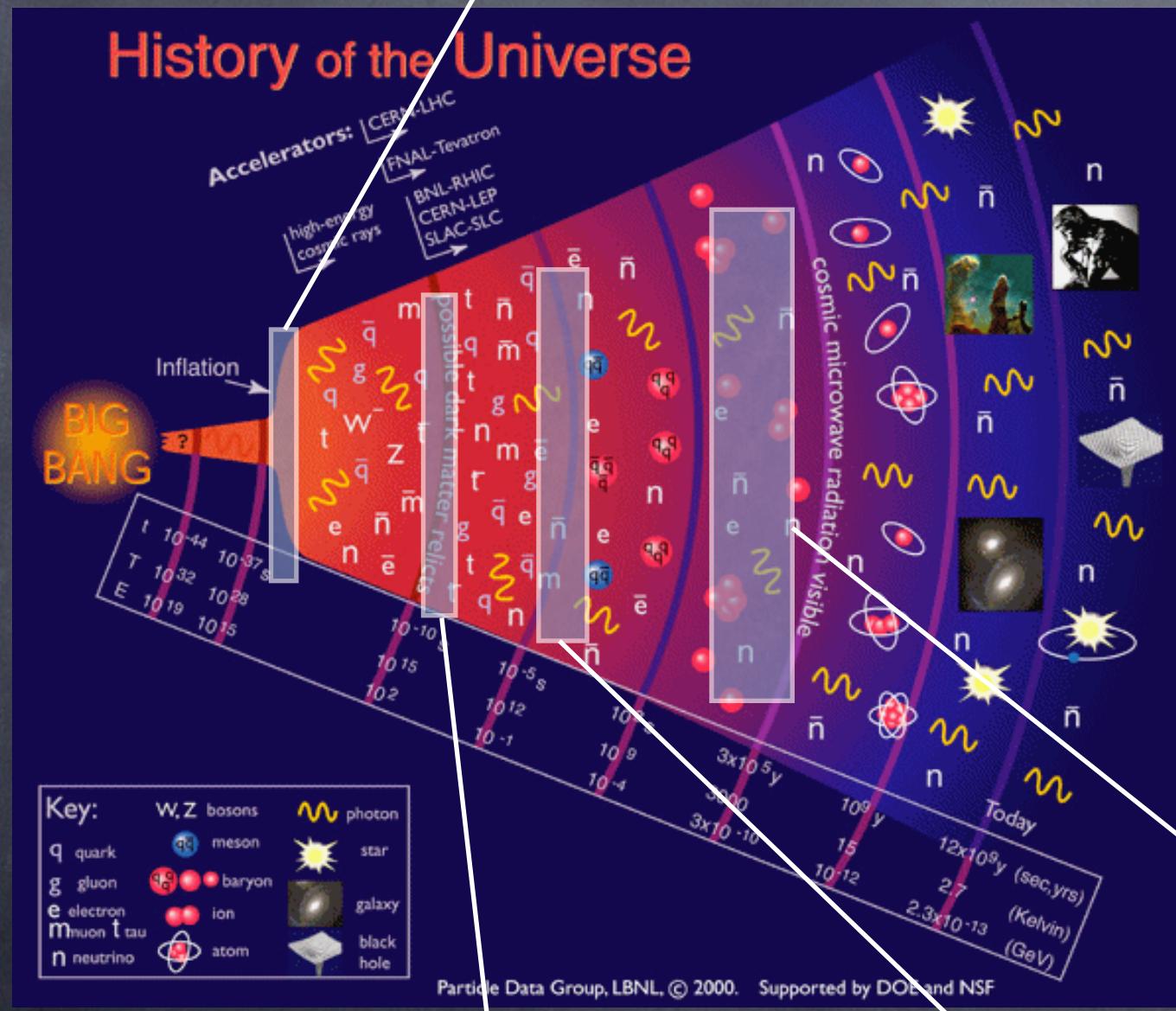
$z=0$



$z=4$

$z=0$

inflation (a-causal generation)



PRIMORDIAL GENERATION

(causal generation)

plasma dynamics

EW phase transition

QCD phase transition

Generation prior to recombination

GENERATION BY PLASMA DYNAMICS + VORTICITY

$$\begin{aligned}\partial_t B + \nabla \times E &= 0 & J &= en(v_p - v_e) & \square B &= 4\pi en(\Omega_p - \Omega_e) \\ \nabla \times B - \partial_t E &= 4\pi J\end{aligned}$$

electrons do Thomson scattering (Harrison 1973)

- ⌚ vorticity by wiggly strings, by second order perturbations?
- ⌚ PROBLEM: very small scales?

Vachaspati and Vilenkin 1991, Davis and Dimopoulos 2005, Battfeld et al 2007...
Berezhiani and Dolgov 2003, Gopal and Sethi 2004, Matarrese et al 2004, Takahashi et al 2005...

Generation prior to recombination

PRIMORDIAL PHASE TRANSITIONS

- FIRST ORDER charge separation or currents at bubble walls + amplification by MHD turbulence (both EW and QCD)

Hogan 1983, Quashnock et al 1989, Cheng and Olinto 1994, Baym et al 1996, Sigl et al 1996, Ahonen and Enqvist 1997, Stevens and Johnson 2010...

- SECOND ORDER EW generated by the symmetry breaking connected to baryogenesis $h \sim -n_b/\alpha$

Vachaspati 1991, Davidson 1996, Cornwall 1997, Grasso and Riotto 1997, Hindmarsh and Everett 1997, Tornkvist 1998, Field and Carroll 1998, Vachaspati 2001, Campanelli and Giannotti 2005, Copi et al 2008, Diaz-Gil et al 2008...

- PROBLEM : causal, so very small scales $L \leq \eta_{EW} \simeq 10^{-4}$ pc

Generation prior to recombination

INFLATION

- A-CAUSAL : generated at all scales
- PROBLEM : need to break conformal invariance $\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
otherwise vacuum fluctuations not amplified
- coupling of em field to the metric, to the inflaton, in string theory context, assuming a massive photon, by parametric resonance during preheating, introducing a charged scalar field...

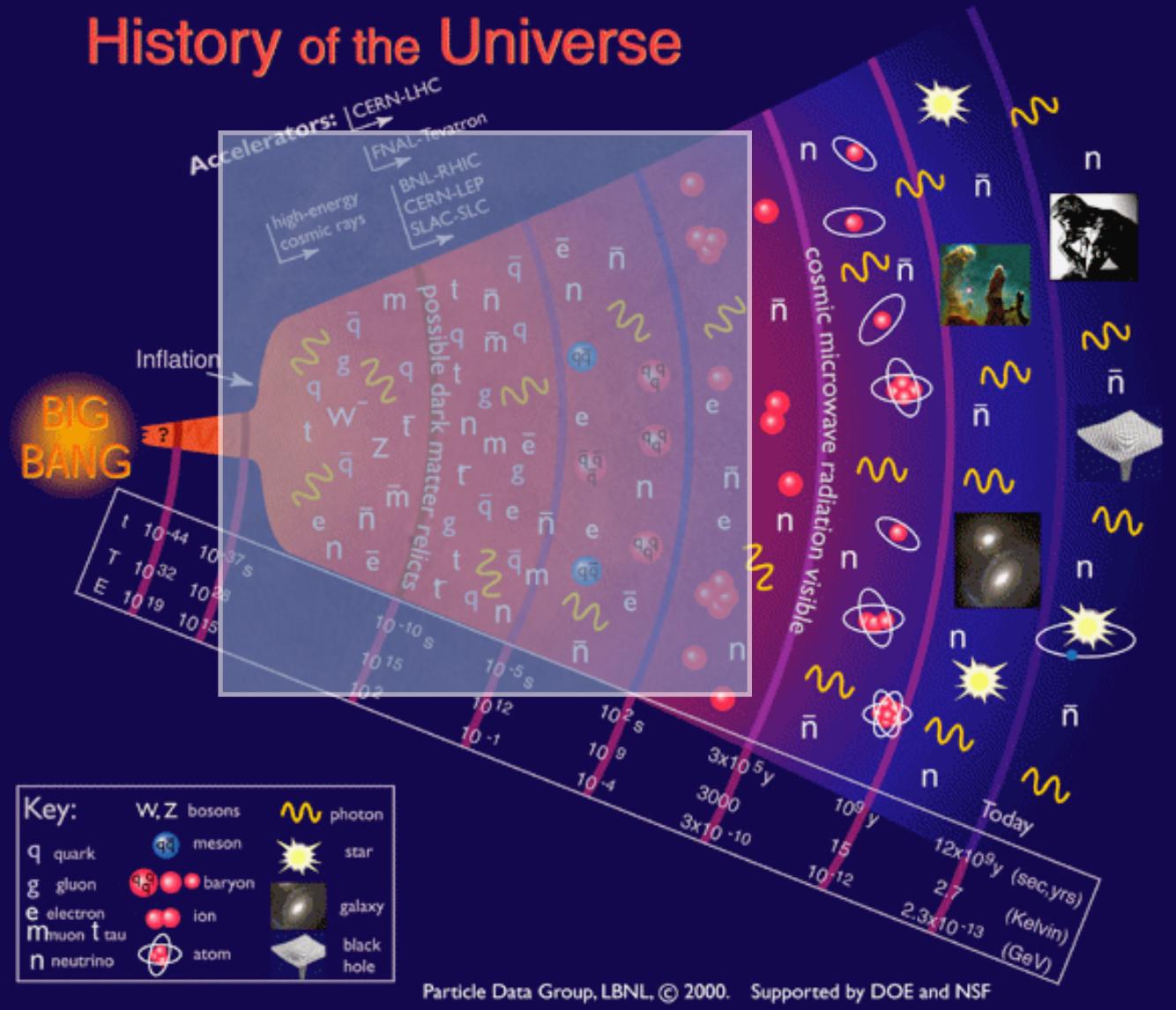
$$RF_{\mu\nu}F^{\mu\nu} \quad e^{\alpha\phi}F_{\mu\nu}F^{\mu\nu} \quad f(\phi)F_{\mu\nu}F^{\mu\nu} \quad m^2A_\mu A^\mu$$

Turner and Widrow 1988, Ratra 1992, Giovannini and Shaposhnikov 2000, Dimopoulos et al 2002, Bamba and Yokoyama 2004, Martin and Yokoyama 2007, Campanelli et al 2008, Demozzi et al 2009, Durrer et al 2010...

- PROBLEM : amplitude very model dependent

OUTLINE OF THE SEMINAR:

History of the Universe



IF THEY ARE
PRIMORDIAL

MODEL AND
EVOLUTION

CONSTRAINTS

OBSERVATIONAL
EFFECTS

Primordial magnetic field – Model

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

FRW : homogeneity and isotropy

$$ds^2 = a(t)^2(-dt^2 + dx_i dx^i)$$

$$T_{\mu\nu} = \begin{pmatrix} -\rho g_{00} & 0 \\ 0 & Pg_{ij} \end{pmatrix}$$

- MF breaks FRW symmetries $T_{\mu\nu}^B = \begin{pmatrix} -\frac{B^2}{2} g_{00} & 0 \\ 0 & -\frac{B^2}{2} g_{ij} - B_i B_j \end{pmatrix}$
- first order perturbation in FRW $G_{\mu\nu} + \delta G_{\mu\nu} = 8\pi G (T_{\mu\nu} + T_{\mu\nu}^B)$
- Stochastic field, statistically homogeneous, isotropic and gaussian

$$\langle B_i \rangle = 0 \quad \langle B^2 \rangle \neq 0$$

Primordial magnetic field – Model

Power spectrum

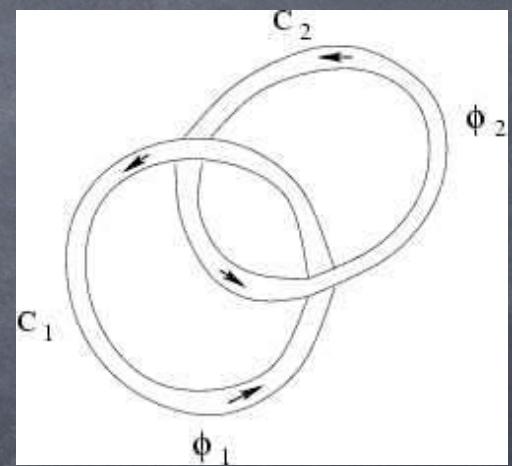
$$\langle B_i(\mathbf{k}) B_j^*(\mathbf{q}) \rangle = \delta(\mathbf{k} - \mathbf{q}) [(\delta_{ij} - \hat{k}_i \hat{k}_j) S(k) + i \epsilon_{ijk} \hat{k}^m A(k)]$$

energy density $E_B = \int_0^\infty dk k^2 S(k)$

helicity density $H = \int_0^\infty dk k A(k)$

$$H = \frac{1}{V} \int_V d^3x \mathbf{A} \cdot \mathbf{B}$$

Divergence free



Mean amplitude of the
MF on a given scale λ

$$B_\lambda^2 = \int dk k^2 S(k) e^{-k^2 \lambda^2}$$

Primordial magnetic field – Model

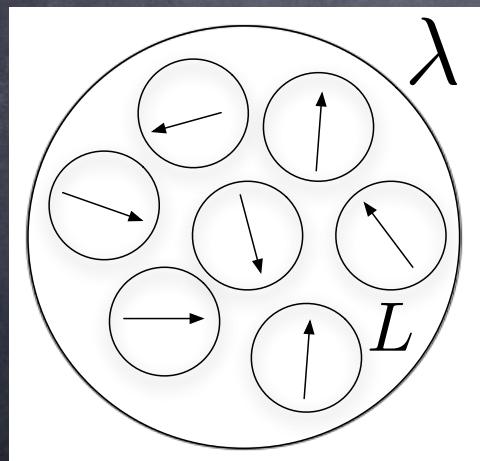
CAUSAL FIELD: $\langle B_i(\mathbf{x})B_j(\mathbf{x} + \mathbf{r}) \rangle = 0$ for $r > L$ $L \leq \text{horizon}$

correlation function compact support \rightarrow power spectrum analytic

$$S(k) \propto k^2, k^4 \dots$$

DIVERGENCE FREE IMPLIES
NO RANDOM WALK: $n \neq 0$

$$B_\lambda^2 = B_L^2 \left(\frac{L}{\lambda} \right)^{n+3}$$



\rightarrow Cluster scale today 0.1 Mpc

\rightarrow Horizon scale at generation 10^{-4} pc

extra suppression at large scales, disfavour causal generation

Primordial magnetic field – Evolution

$$ds^2 = a(t)^2(-dt^2 + dx_i dx^i)$$

conformal
transformation $g_{\mu\nu} = a(t)^2 \eta_{\mu\nu}$ \longrightarrow flat spacetime

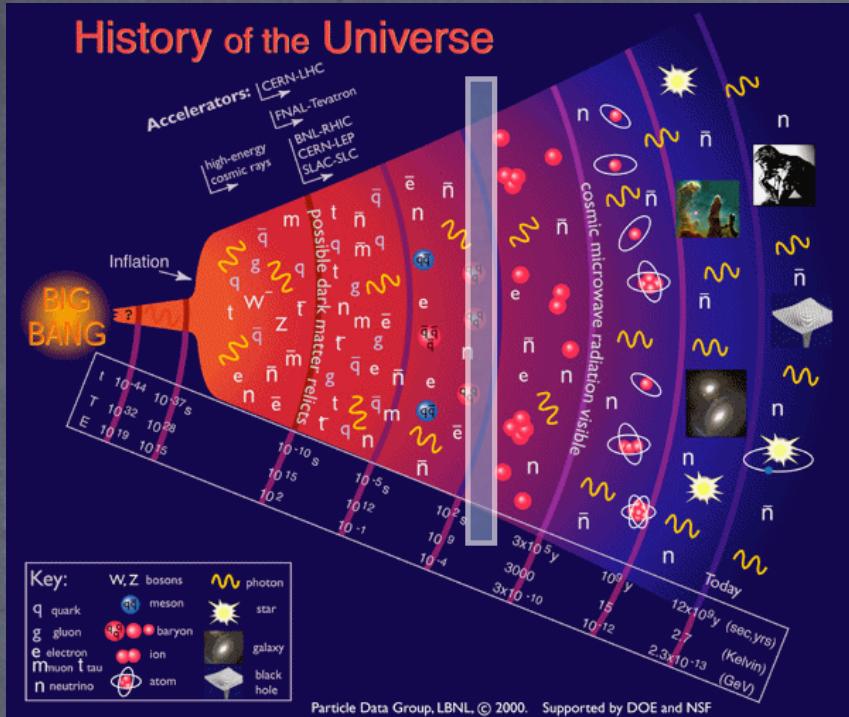
The equation of motions are the same for $B = a(t)^2 \mathcal{B}$

induction equation: $\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\Delta B}{4\pi\sigma}$

IDEAL MDH limit $\sigma \rightarrow \infty$: flux and helicity are conserved

$$\mathcal{B} \propto a^{-2}(t)$$

Primordial magnetic field – Evolution



neutrino decoupling

electrons non relativistic

TURBULENT PHASE

$$\nu \simeq \ell_{\nu e} \quad \text{Re} \gg 1$$

Turbulent cascade

VISCOUS PHASE

$$\nu \simeq \ell_{\gamma e} \quad \text{Re} \simeq 1$$

MHD waves in viscous fluid:
damping of magnetic energy

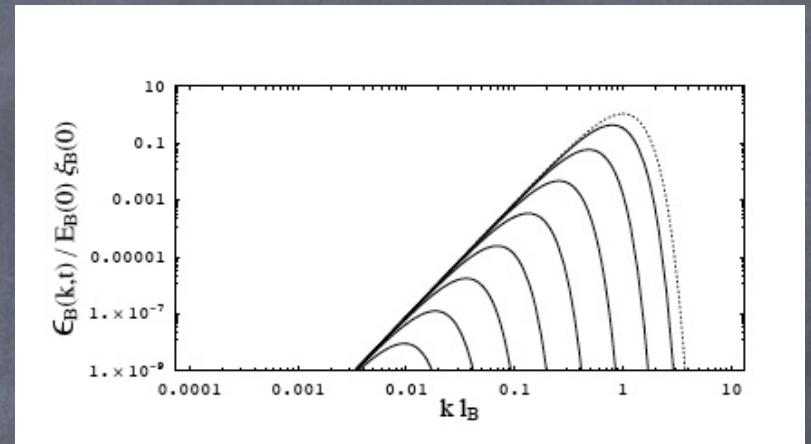
Jedamzik et al 1996, Ahonen and Enqvist 1996, Subramanian and Barrow 1997, Banerjee and Jedamzik 2004, CC et al 2009...

Primordial magnetic field – Evolution

TURBULENT PHASE

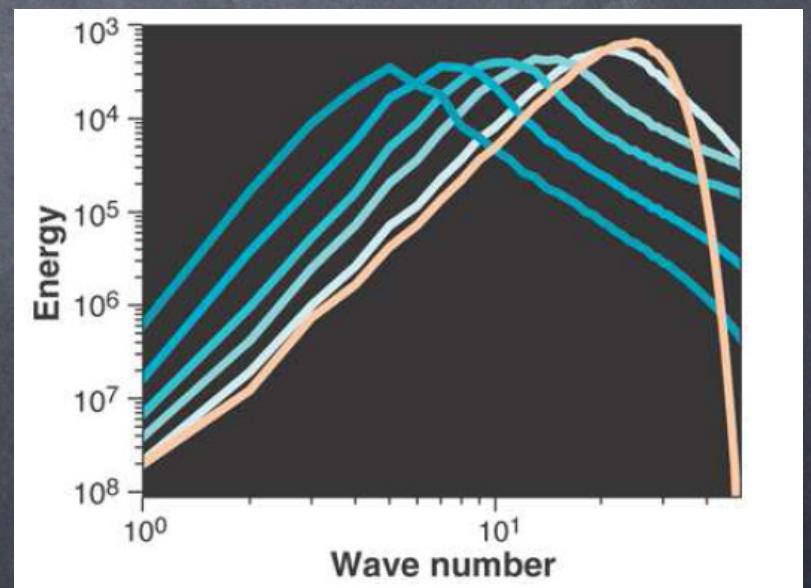
- non-helical field: DIRECT CASCADE

magnetic energy is dissipated
correlation scale grows



- helical field: INVERSE CASCADE

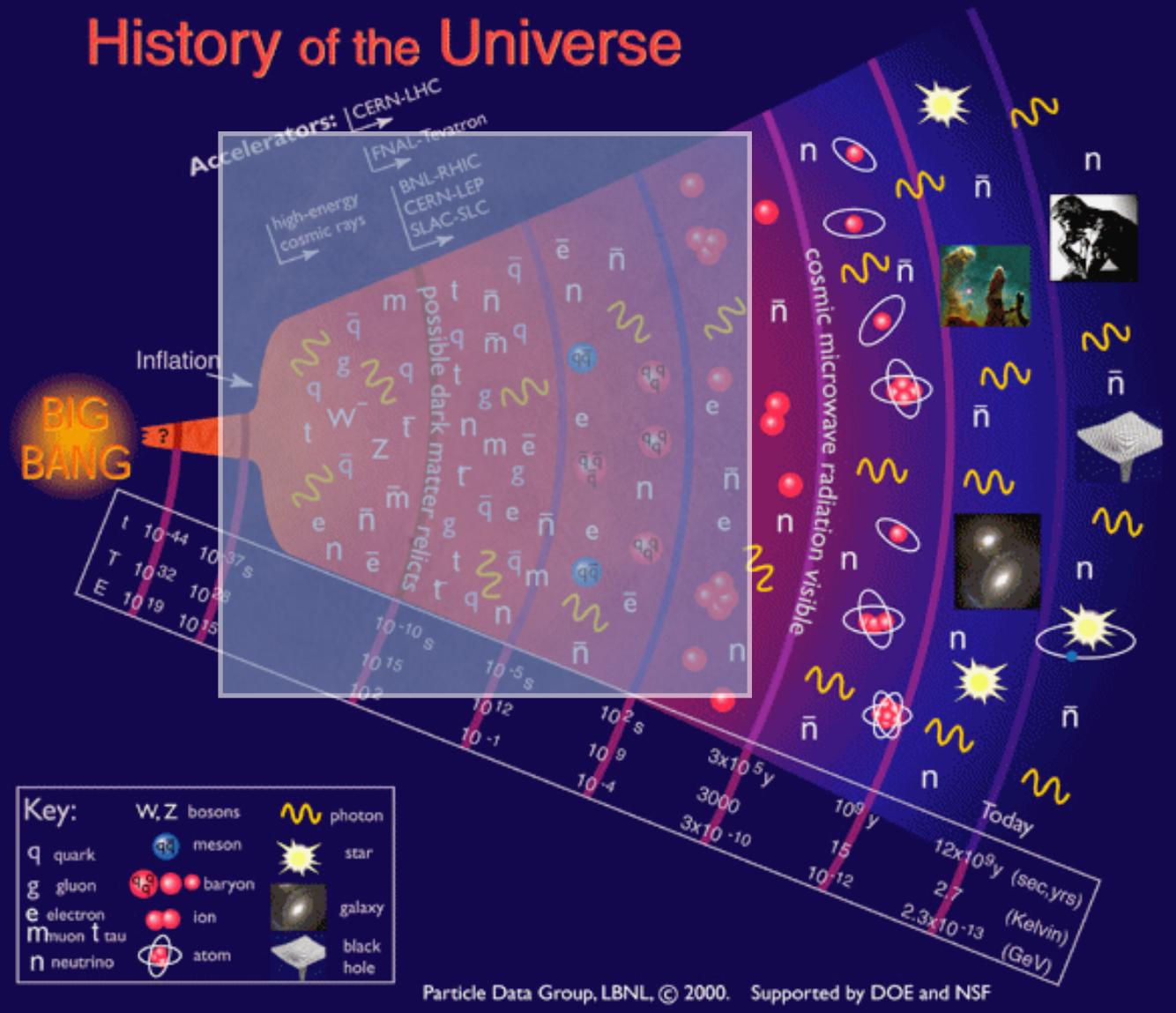
Magnetic energy is transferred to larger scales
correlation scale grows



Christensson et al 2002, Banerjee and
Jedamzik 2004, Campanelli 2007...

OUTLINE OF THE SEMINAR:

History of the Universe



IF THEY ARE
PRIMORDIAL

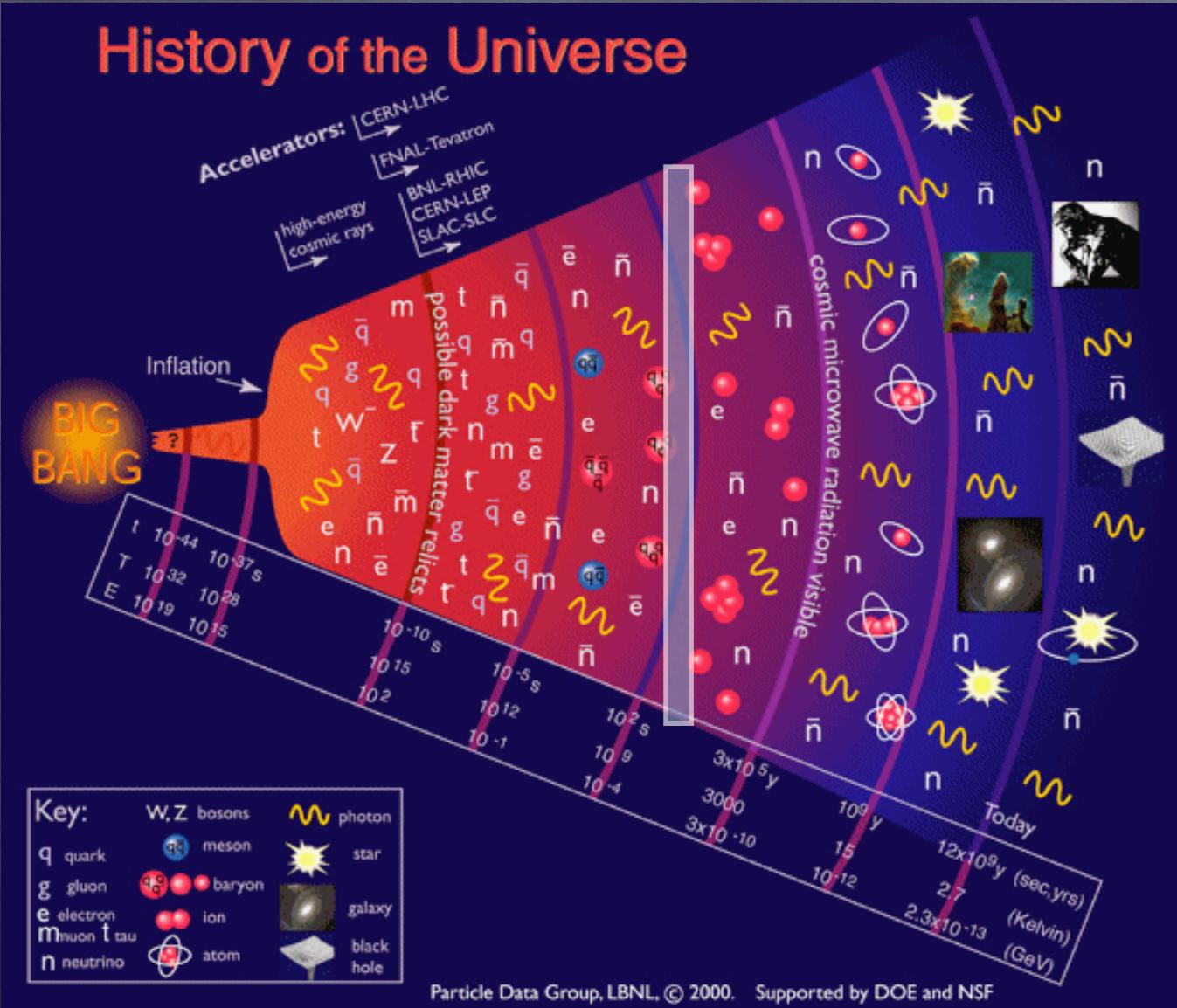
MODEL AND
EVOLUTION

CONSTRAINTS

OBSERVATIONAL
EFFECTS

NUCLEOSYNTHESIS

History of the Universe



$$G_{\mu\nu} = 8\pi G T_{\mu\nu} \longrightarrow \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3} \rho_{\text{tot}}$$

- Abundance of neutrons depends on universe expansion
- MF influences universe expansion
- Abundances of elements constrains MF intensity

Primordial magnetic field – Constraints

$$B \simeq 10^{-9} \text{ Gauss} \quad \text{or} \quad 10^{-21} \text{ Gauss} \quad \text{at about 100 kpc}$$

- Generation at EWPT (100 GeV) causal, $n=2$
non-helical $B_{0.1\text{Mpc}} < 10^{-31} \text{ G}$
helical $B_{0.1\text{Mpc}} < 10^{-23} \text{ G}$

- Generation at inflation 10^{14} GeV :

non-helical $n = 0$ $B_{0.1\text{Mpc}} < 10^{-37} \text{ G}$

$n \rightarrow -3$ $B_{0.1\text{Mpc}} < 10^{-9} \text{ G}$

helical $n = 0$ $B_{0.1\text{Mpc}} < 10^{-28} \text{ G}$

$n = -1.8$ $B_{0.1\text{Mpc}} < 10^{-18} \text{ G}$

- Generation at QCDPT (100 MeV) causal, $n=2$

non-helical $B_{0.1\text{Mpc}} < 10^{-23} \text{ G}$

helical $B_{0.1\text{Mpc}} < 10^{-19} \text{ G}$

CC and Durrer 2001,
CC et al 2009

Primordial magnetic field – Constraints

$$B \simeq 10^{-9} \text{ Gauss} \quad \text{or} \quad 10^{-21} \text{ Gauss} \quad \text{at about 100 kpc}$$

- Generation at EWPT (100 GeV) causal, n=2

non-helical	$n = 0$	$B_{0.1\text{Mpc}} < 10^{-31} \text{ G}$
helical	$n \rightarrow -3$	$B_{0.1\text{Mpc}} < 10^{-23} \text{ G}$
- Generation at inflation 10^{14} GeV :

non-helical	$n = 0$	$B_{0.1\text{Mpc}} < 10^{-37} \text{ G}$
helical	$n = 0$	$B_{0.1\text{Mpc}} < 10^{-28} \text{ G}$
	$n \rightarrow -3$	$B_{0.1\text{Mpc}} < 10^{-9} \text{ G}$
	$n = -1.8$	$B_{0.1\text{Mpc}} < 10^{-18} \text{ G}$

← Ok without dynamo

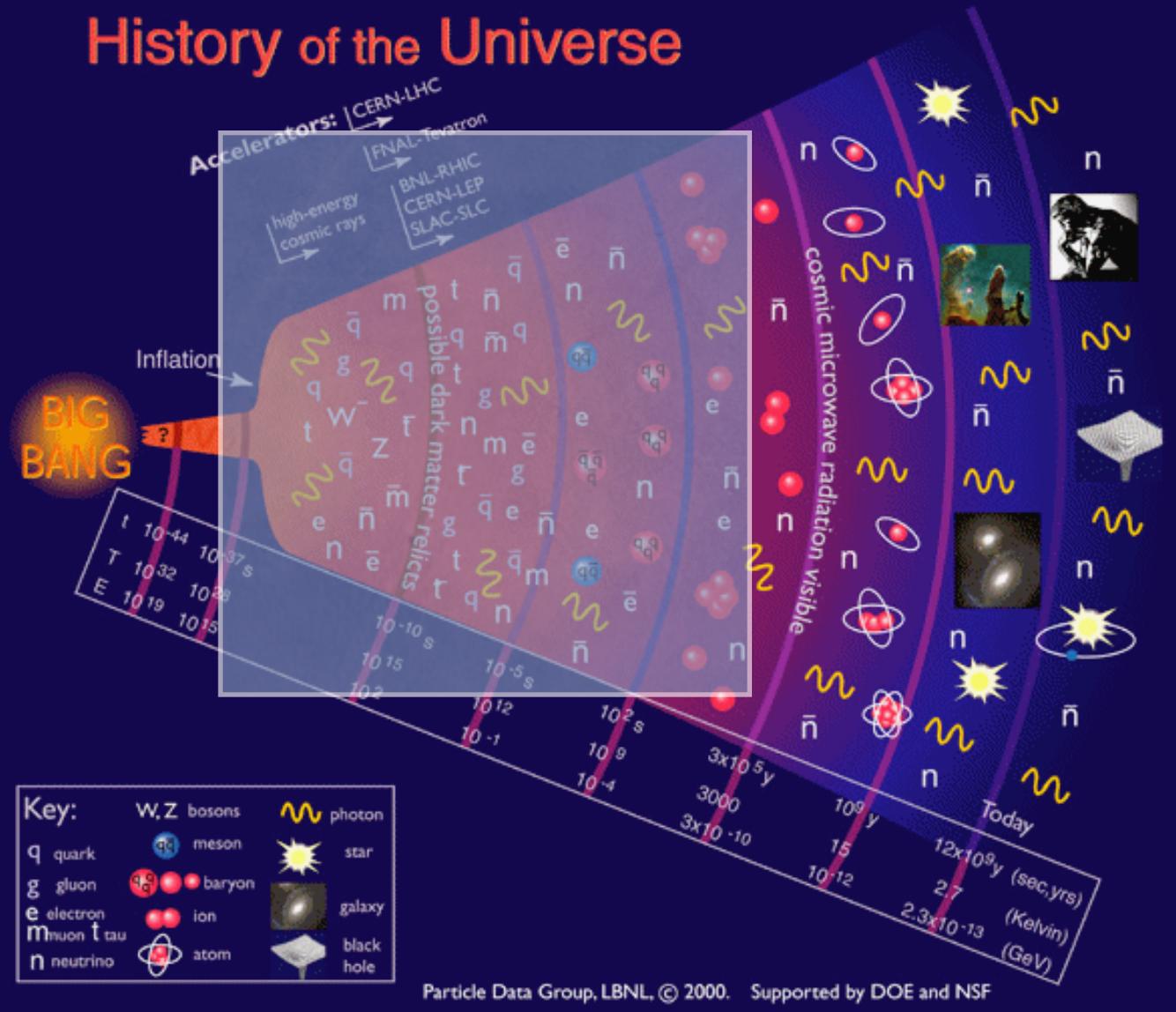
← Ok with dynamo
- Generation at QCDPT (100 MeV) causal, n=2

non-helical	$B_{0.1\text{Mpc}} < 10^{-23} \text{ G}$
helical	$B_{0.1\text{Mpc}} < 10^{-19} \text{ G}$

← CC and Durrer 2001,
CC et al 2009

OUTLINE OF THE SEMINAR:

History of the Universe



IF THEY ARE
PRIMORDIAL

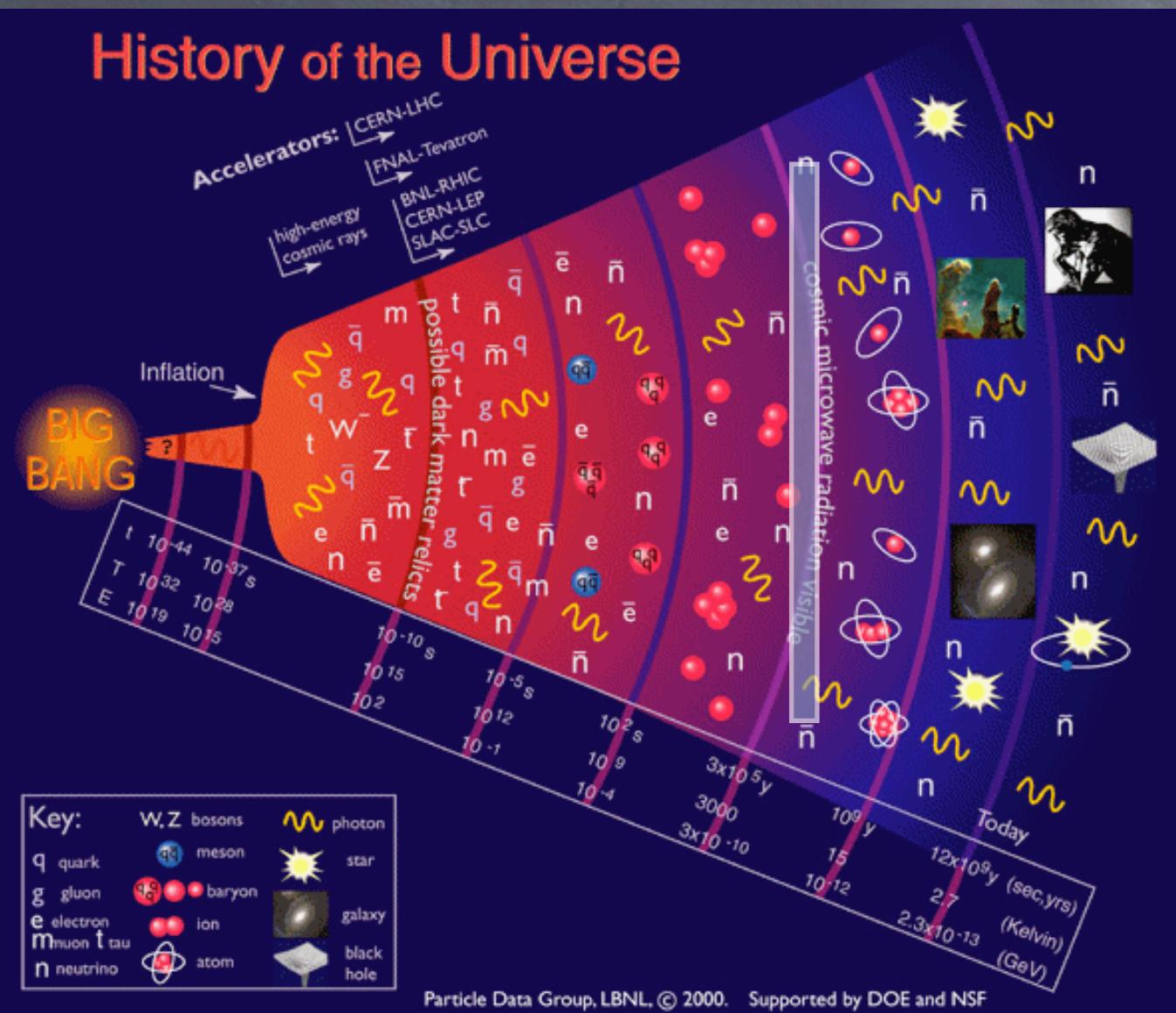
MODEL AND
EVOLUTION

CONSTRAINTS

OBSERVATIONAL
EFFECTS

Primordial magnetic field – Observational effects

History of the Universe



MF breaks
FRW
symmetries

CMB measures the isotropy of the universe

$$\frac{\delta T}{T} \sim 10^{-5}$$

Primordial magnetic field – CMB effects

$$\delta G_{\mu\nu} = 8\pi G(\delta T_{\mu\nu} + T_{\mu\nu}^B)$$

radiation, baryons, dark matter, neutrinos

MF energy momentum tensor:
scalar, vector, tensor modes

$$\ell^2 C_\ell \sim \left(\frac{\Omega_B}{\Omega_{\text{rad}}} \right)^2 \sim 10^{-14} \left(\frac{B}{10^{-9} \text{Gauss}} \right)^4$$

CMB constraints of the
order of the nanoGauss

- MF + baryons : MHD waves (magnetosonic, Alfvén)
- vector mode (Alfvén waves) survives damping at small scales

$$L_D \simeq V_A L_{\text{Silk}} \quad V_A \simeq \sqrt{\frac{\Omega_B}{\Omega_{\text{rad}}}}$$

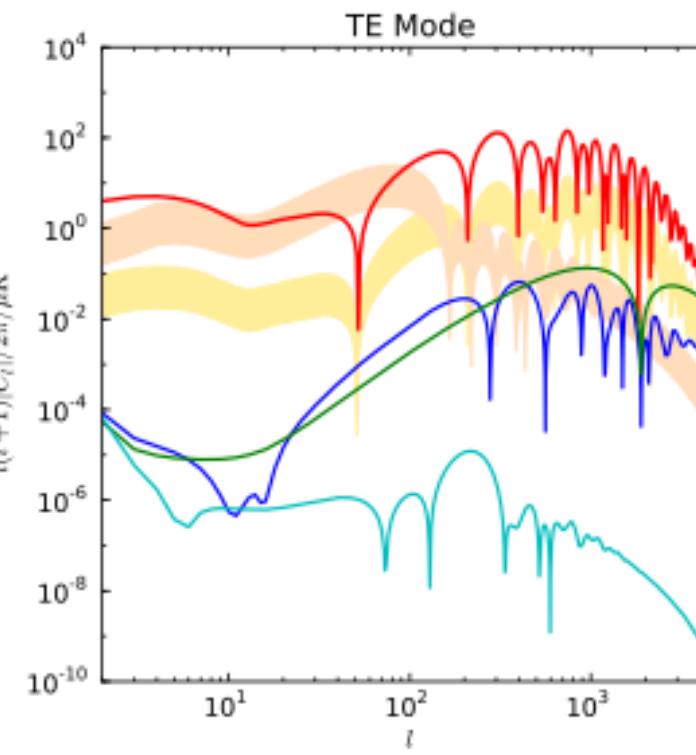
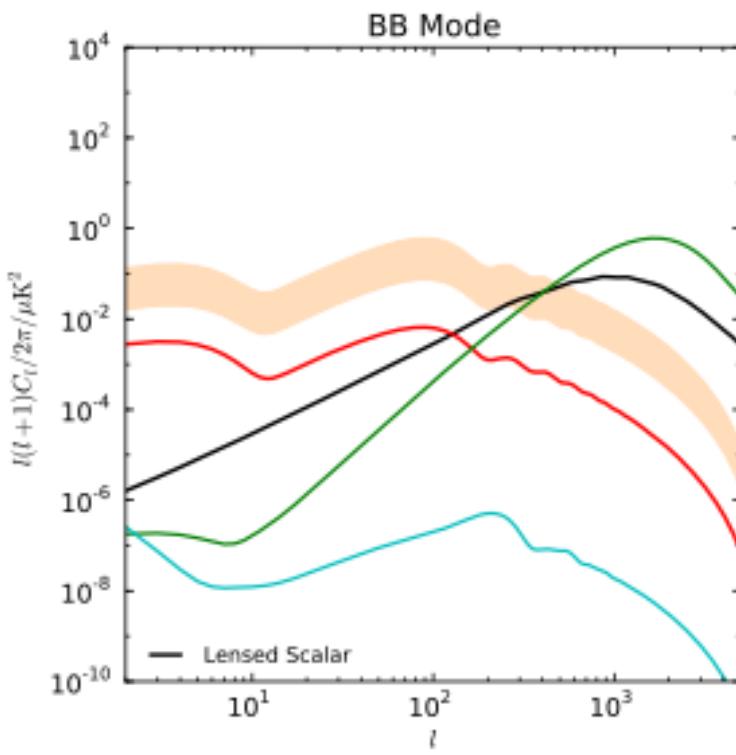
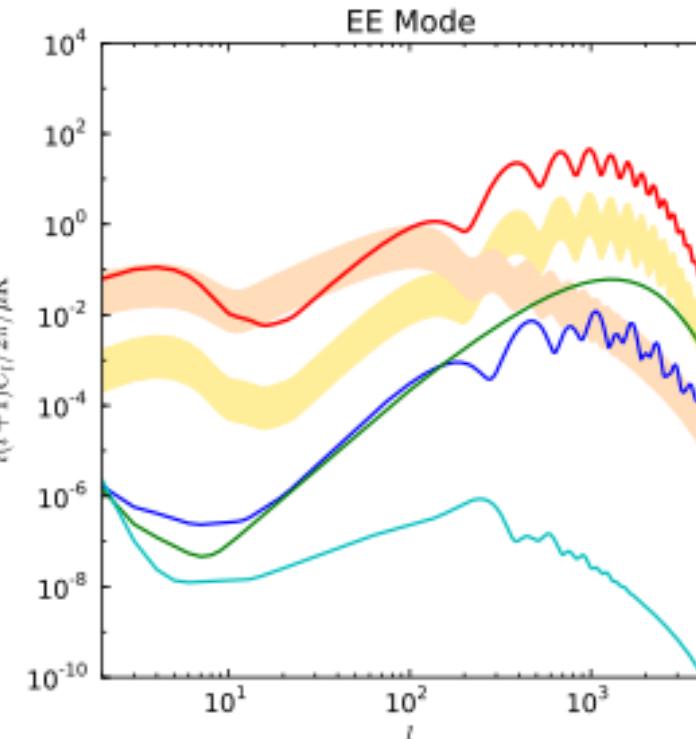
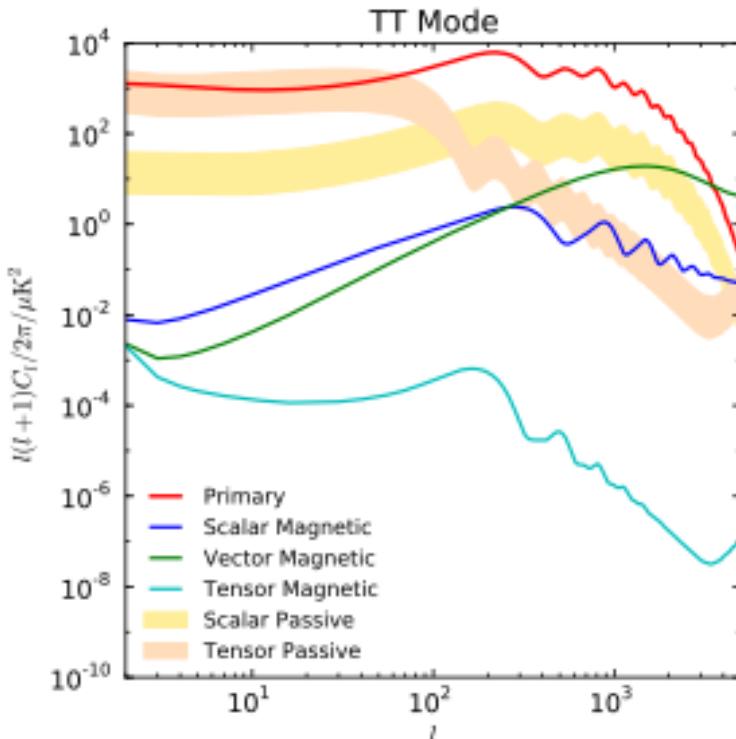
Subramanian and
Barrow 2002

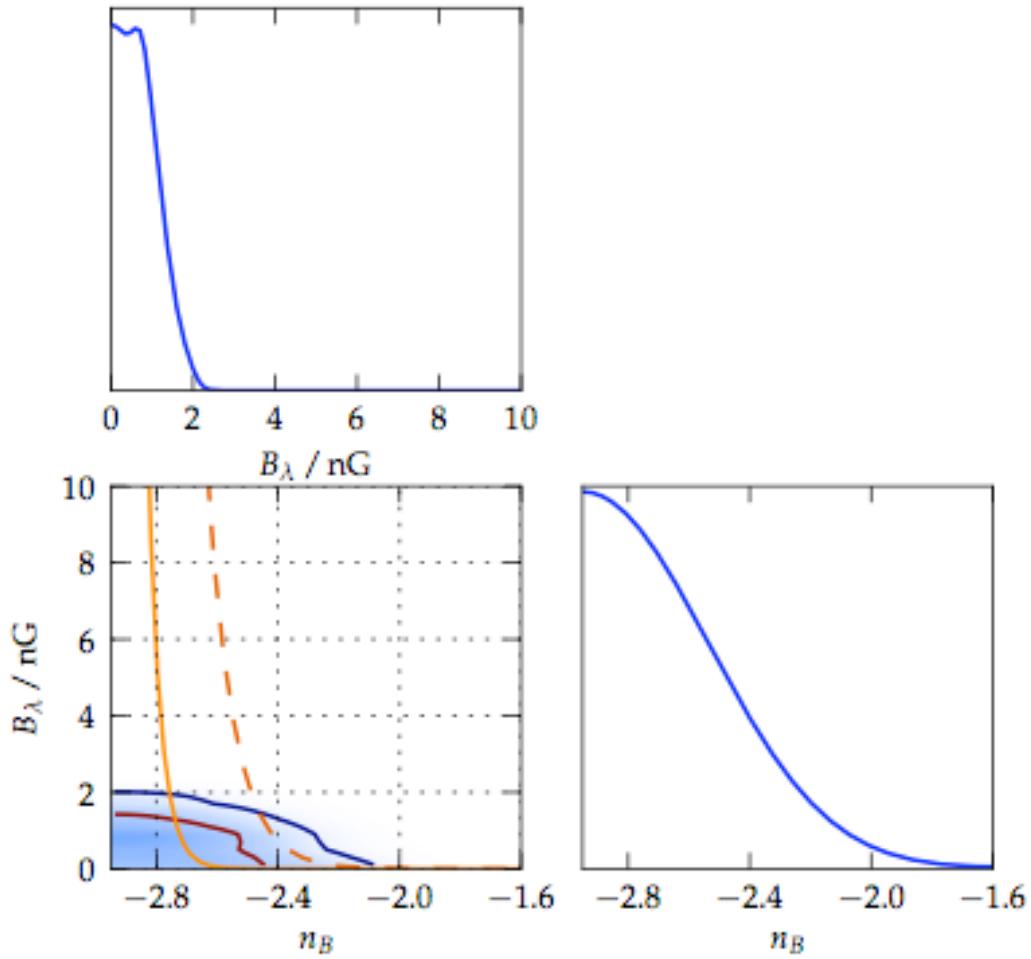
affects temperature and B polarisation at high multipoles

$$B_{1\text{Mpc}} = 4.7 \text{ nG}$$

$$n = -2.9$$

Shaw and Lewis '10
 Finelli and Paoletti '10
 Yamakazi et al '08
 Finelli et al '08
 Giovannini and Kunze '07
 Kahnashvili and Ratra '06
 Lewis '04
 Mack et al '02
 Koh and Lee '02...





constraints on the MF
intensity and spectral index
from CMB and matter
power spectrum

$$B_{1\text{Mpc}} \leq 1.6 \text{ nG} \quad n \leq -2$$

Shaw and Lewis 2010

Primordial magnetic field – CMB effects

- Parity odd cross-correlations from helical field Pogosian et al 2001, CC et al 2004

$$\ell^2 C_\ell^{TB} \sim \ell^2 C_\ell^{EB} \sim 10^{-11} \text{ at } \ell = 50$$

- Faraday rotation of CMB polarisation Kosowsky and Loeb 1996, Campanelli et al 2004, Kosowsky et al 2005...

rotation of E in B: $\ell^2 C_\ell^B \sim 10^{-14}$ at $\ell = 10^4$, $\nu = 30\text{GHz}$

- Non-gaussianity: B is gaussian so the source B^2 is not.
WMAP constraints :

$$\frac{b_{\ell\ell\ell}}{(C_\ell)^{3/2}} = \mathcal{O}(1)$$

$$\begin{aligned}\sqrt{\langle B^2 \rangle} &\leq 9 \text{ nGauss} & \text{for } n = -2.9 \\ \sqrt{\langle B^2 \rangle} &\leq 25 \text{ nGauss} & \text{for } n = -2 \\ \sqrt{\langle B^2 \rangle} &\leq 20 \text{ nGauss} & \text{for } n = 2\end{aligned}$$

CC et al 2009

Brown and Crittenden 2005, Seshadri and Subramanian 2009, Trivedi et al 2010, Shiraishi et al 2010

Conclusions

The origin of MF observed in astrophysical objects is still unclear

The lower bound on the MF amplitude in IGM by Fermi points toward primordial generation (non causal) or ejection at very large scales

Improvements in observations:

- ⦿ PLANCK: detect B polarisation and large multipoles
parity-odd cross-correlations?
non-gaussianity?
- ⦿ SKA radiotelescope: all-sky rotation measure survey
evolution of magnetised structure from $z>3$

Improvements in theory:

- ⦿ deeper understanding of generation from ejection or biermann battery during structure formation
- ⦿ CMB signal : initial conditions and non-gaussianity